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INSTALLATION AND OPERATION OF PARTICLE TRANSPORT SIMULATION PROGRAMS TO MODEL THE DETECTION AND MEASUREMENT OF SPACE RADIATION BY SPACE-BORNE SENSORS

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13. ABSTRACT (Maximum 200 words)
This document is a report of the technical progress made during the period 01 Aug. 2001 - 31 July 2002 in the areas of: (1) research, evaluation and adaptation of particle transport simulation programs for modeling the detection and measurement of space radiation by space-borne sensors; (2) construction of realistic flight sensor computer models; (3) performance of particle transport calculations; (4) space-borne dosimeter simulation studies; (5) studies of scattering of grazing incidence protons from surfaces of material constituents of space-borne X-ray telescopes. The computer programs ITS/ACCEPT and MCNPX were applied to the modeling of the CEASE and HEP sensors. Shown in this report are listings of input and output files, with geometry/materials drawings, for the various simulation programs, annotated computer code listings showing program modifications, and partial listings of computer code outputs.

14. SUBJECT TERMS Electron and proton transport; Monte Carlo simulation; Space-borne sensor modeling; ITS/ACCEPT Code; MCNPX Code; Dosimeters; grazing angle proton scatter

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1. INTRODUCTION

The effort to be described in this report was performed as partial fulfillment of two primary objectives: (1) perform computer simulations of charged particle transport, energy and charge deposition in satellite-borne instrumentation used in research efforts of the Air Force Research Laboratory/Space Weather Center of Excellence (AFRL/VSBXR) to detect and characterize (by type, energy, intensity, *etc.*) particles associated with ionizing radiation in space; (2) transfer this simulation capability to AFRL/VSBXR and provide advice to Air Force researchers on its use; and (3) perform studies of transport code predictions of grazing angle proton scattering. In the following sections, we provide descriptions and examples of particle transport simulations and their application to problems of interest to AFRL/VSBXR.

2. ELECTRON TRANSPORT MODELING

2.1 CRRES Dosimeter Models – MCNPX and ITS/ACCEPT

A series of flux and dose response functions for electrons and protons were calculated by Auchampaugh and Cayton [1] for electron, secondary photon and proton transport in the CRRES (Combined Release and Radiation Effects Satellite) dosimeters. The calculations were made in 1992 using the then current versions of MCNP[2] for electron and photon transport and LAHET[3] for the proton transport. Since that time, the MCNP and LAHET codes have been superceded by MCNPX[4]. Also, our experience has shown that the electron transport calculations can in general be performed more efficiently using ITS/ACCEPT[5] rather than MCNPX. For this reason, as well as recognition of significantly (since 1992) reduced computation cost, we undertook to repeat some of the electron/photon transport calculations of [1] using both the MCNPX and ACCEPT codes, thus providing an "in-house" Air Force capability to perform these and other simulations as may be needed in the future.

The original MCNP geometry files from [1] for the CRRES_D1, D2, D3 and D4 dosimeters were supplied by D. Brautigam (AFRL)[6]. The D1 and D2 files are shown in Figures 1 and 2, respectively.

We used the visual editor program VISED[7]for MCNP input files to assist in the interpretation of the geometry files shown in Figures 1 and 2. This visualization is shown in Figures 3 and 4, which are the diagrams for the CRRES_D1 cell and surface configurations, respectively. VISED provides the color rendering to distinguish among the five materials specified by the "mX" (X=1-Si; 2-Al; 3-Al_2O_3; 4-Ni; 5-W,Fe alloy). records in the geometry files.

```
Geometry for CRRES dosimeter dome 1
-- 11 Feb 92
1    1 -2.33 11 -10 -3
2    1 -2.33 11 -10 3 23 -24 25 -26
3    0 11 -10 (-23:24:-25:26) -2
4    0 10 -2
5    2 -2.700 2 -1 10
6    2 -2.700 2 -1 11 -10
7    0 12 -11 -22
8    0 13 -12 -5
9    3 -3.700 12 -11 22 -8
10   2 -2.700 12 -11 8 -7
11   2 -2.700 13 -12 5 -7
12   4 -8.900 14 -13 -5
13   2 -2.700 14 -13 5 -7
14   2 -2.700 15 -14 -7
15   5 -18.30 17 -15 -6
16   2 -2.700 17 -15 6 -7
17   2 -2.700 17 -16 7 -9
18   0 16 -11 7 -9
19   0 11 1 -18
20   0 ((11 18):(-11 9):-17) -20
21   0 20
22   0 21

1    so 1.22936
2    so 1.01981
3    cz 0.05093
4    cz 0.76200
5    cz 0.32385
6    cz 1.11125
7    cz 1.22936
8    cz 0.50800
9    cz 1.46812
10   pz 0.04030
11   pz 0.00000
12   pz -0.07620
13   pz -0.10668
14   pz -0.15748
15   pz -0.31496
16   pz -0.94996
17   pz -1.58496
18   so 1.46812
19   so 1.32000
20   so 50.0
21   pz -0.0000001
22   cz 0.06350
23   px -0.09525
24   px 0.09525
25   py -0.09525
26   py 0.09525

 mode p e
 imp:p,e  1 19r 0 1
 m1    14000 1.
 m2    13000 1.
 m3    8000 -0.47075 13000 -0.52925
 m4    28000 1.
 m5    74000 -0.95  26000 -0.05
 sdef   sur=19 ccc=22 nrm=-1. dir=d1
par=3 erg=5.0
 sb1 -21 1
 sp1 -21 1
f108:p,e  1
e108   0. .049 .051 .125 .193 .263 .336
.408 .480 .549 .622 .694 .765
   .839 .910 0.979 1.020 1.28 1.91 2.56
3.20 3.84 4.48 5.12 5.74
   6.37 7.01 7.67 8.30 8.94 9.57 10.1
41.2 104. t
phys:e 25.5
```

Figure 1. CRRES_D1 Dosimeter run file, LANL Version[1], for MCNP[2].

```
Geometry for CRRES dosimeter dome 2
-- 11 Feb 92
1     1 -2.33 11 -10 -3
2     1 -2.33 11 -10 3 23 -24 25 -26
3     0 11 -10 (-23:24:-25:26) -2
4     0 10 -2
5     2 -2.700 2 -1 10
6     2 -2.700 2 -1 11 -10
7     0 12 -11 -22
8     0 13 -12 -5
9     3 -3.700 12 -11 22 -8
10    2 -2.700 12 -11 8 -7
11    2 -2.700 13 -12 5 -7
12    4 -8.900 14 -13 -5
13    2 -2.700 14 -13 5 -7
14    2 -2.700 15 -14 -7
15    5 -18.30 17 -15 -6
16    2 -2.700 17 -15 6 -7
17    2 -2.700 17 -16 7 -9
18    0 16 -11 7 -9
19    0 11 1 -18
20    0 ((11 18):(-11 9):-17) -20
21    0 20
22    0 21

1     so 1.74498
2     so 1.15443
3     cz 0.12741
4     cz 0.76200
5     cz 0.32385
6     cz 1.54813
7     cz 1.74498
8     cz 1.14300
9     cz 1.90500
10    pz 0.04340
11    pz 0.00000
12    pz -0.07620
13    pz -0.10668
14    pz -0.15748
15    pz -0.31496
16    pz -0.94996
17    pz -1.58496
18    so 1.90500
19    so 1.76000
20    so 50.0
21    pz -0.0000001
22    cz 0.12700
23    px -0.19685
24    px 0.19685
25    py -0.19685
26    py 0.19685

 mode p e
 imp:p,e   1 19r 0 1
 m1     14000 1.
 m2     13000 1.
 m3     8000 -0.47075 13000 -0.52925
 m4     28000 1.
 m5     74000 -0.95   26000 -0.05
 sdef     sur=19  ccc=22  nrm=-1.  dir=d1
par=3 erg=2.00
 sb1 -21 1
 sp1 -21 1
f108:p,e  1
e108    0. .051 .066 .134 .217 .287 .356
.434 .507 .579 .655 .735 .807
   .885 .955 1.035 1.26 1.95 2.58 3.23
3.87 4.51 5.13 5.75
   6.38 7.02 7.66 8.28 8.91 9.83 10.21
42.1 104. t
phys:e  5.5
```

Figure 2. CRRES_D2 Dosimeter run file, LANL Version [1],for MCNP[2].

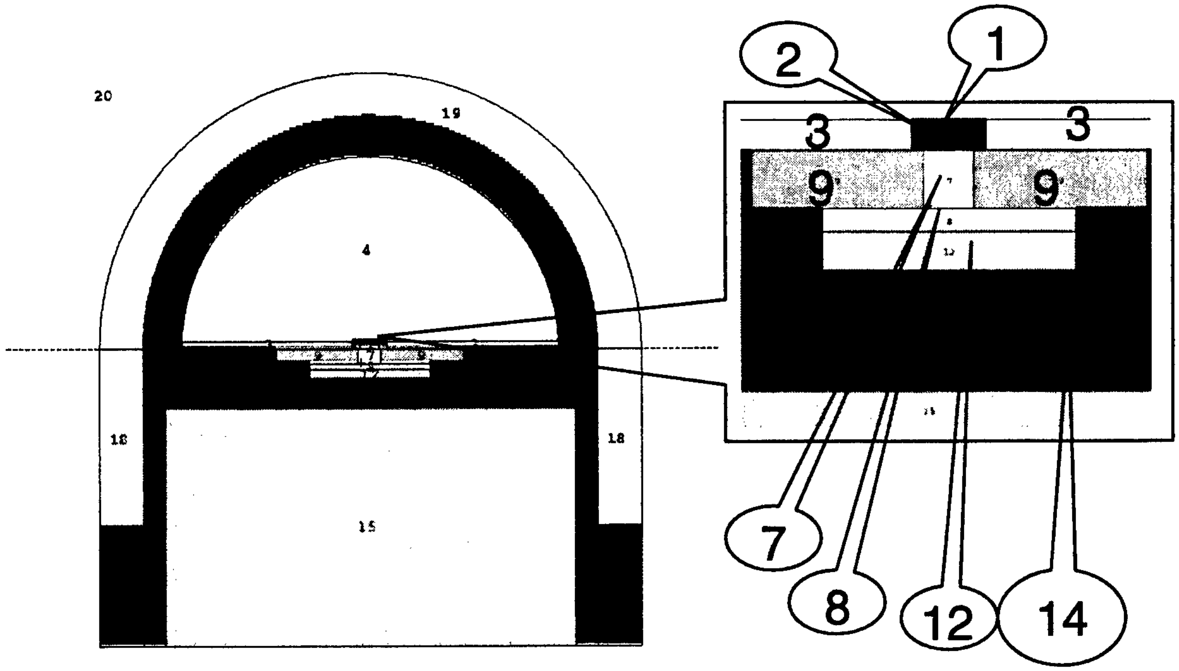

Figure 3. VISED [7] rendering of MCNP cell geometry configuration [1] for CRRES_D1, corresponding to the listing shown in Figure 1.

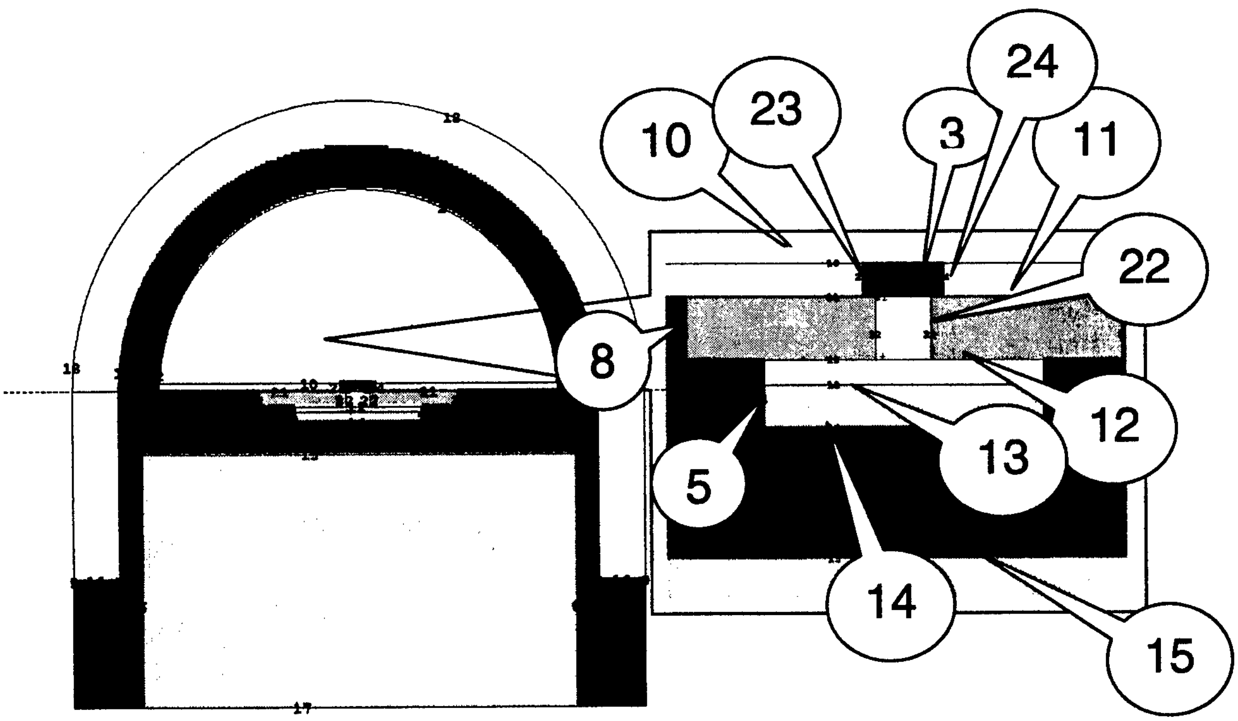

Figure 4. VISED [7] rendering of MCNP surface geometry configuration [1] for CRRES_D1, corresponding to the listing shown in Figure 1.

2.1.1 CRRES_D1 MCNPX Calculations

The authors[1] used a cosine-weighted source (as specified by the "sdef, sb1 and sp1" records of Figures 1 and 2). A cosine-weighted current source corresponds to an isotropic flux of electrons incident on the dome surface. In general, the relationship between current j and flux ϕ is

$$j(\mu) = \mu\phi(\mu) \tag{1}$$

where μ is the cosine of the polar angle between the particle direction and the normal to the surface of incidence.

In the LANL calculations[1] it was assumed that the source particles originated on a hemispherical surface concentric with, but slightly larger than, the dosimeter dome. The CRRES_D1 input file (Figure 1) was used to perform energy deposition calculations in the silicon dosimeter (cell #1 as defined in Figure 1) with MCNPX for four electron source energies, 2, 5, 10, 25 MeV, and the results were compared with those obtained in [1]. These comparisons are shown in Table 1. We computed the energy deposition using two methods: 1) the energy deposition tally supplied by MCNPX; and 2) the method used in [1], a summation over the pulse height distribution of energy deposited. The energy deposition tally capability had not yet been incorporated into MCNP when the calculations of [1] were made. Only the pulse height distribution summation method was available at that time.

Table 1. Energy Deposition (MeV) in CRRES_D1 Dosimeter (Cell #1, Figures 1,3)

SOURCE ENERGY (MEV)	MCNPX METHOD 1 COSINE WEIGHTED	MCNPX METHOD 2 COSINE WEIGHTED	ACCEPT METHOD 1 COSINE WEIGHTED	ACCEPT METHOD 2 COSINE WEIGHTED	AUCHAM-PAUGH & CAYTON [1][1]	ACCEPT METHOD 1 ISOTROPIC IN COSINE	ACCEPT METHOD 2 ISOTROPIC IN COSINE
0.2			2.232e-8	8.791e-9	5.90e-10	0	0
0.3			1.108e-8	0	1.41e-9	9.512e-9	0
0.5			2.698e-8	8.791e-9	3.81e-9	1.708e-8	8.791e-9
1			4.445e-8	2.258e-8	2.33e-7	6.560e-8	2.468e-8
1.5			6.059e-5	6.017e-5	4.27e-5	4.615e-5	4.581e-5
2	1.790e-4	1.856e-4	1.975e-4	1.984e-4	1.07e-3	1.627e-4	1.610e-4
3			3.114e-4	3.106e-4	1.86e-4	2.580e-4	2.558e-4
4			3.060e-4	3.054e-4	2.09e-4	2.477e-4	2.459e-4
5	2.898e-4	3.193e-4	2.668e-4	2.732e-4	2.56e-4	2.166e-4	2.185e-4
6			2.604e-4	2.678e-4	2.73e-4	1.951e-4	2.009e-4
7			2.454e-4	2.564e-4	2.73e-4	1.805e-4	1.861e-4
7.5			2.467e-4	2.552e-4	2.50e-4	1.829e-4	1.893e-4
10	2.828e-4	2.846e-4	2.380e-4	2.899e-4	2.69e-4	1.679e-4	1.737e-4
12.5			2.324e-4	2.415e-4	2.77e-4	1.570e-4	1.689e-4
15			2.261e-4	2.431e-4	2.73e-4	1.572e-4	1.676e-4
20			2.156e-4	2.372e-4	2.63e-4	1.523e-4	1.583e-4
25	2.729e-4	3.222e-4	2.215e-4	2.433e-4	2.60e-4	1.497e-4	1.648e-4

[1] Ref. 1 (Energy Deposition) / Ω

2.1.2 CRRES_D1 ITS/ACCEPT Calculations

The CRRES_D1 geometry and materials data given in Figure 1, along with the VISED diagrams for the cells and surface definitions were used to generate input data files for the ITS/ACCEPT coupled electron/photon Monte Carlo program. The cosine-weighted current source is a standard source option in the ITS/ACCEPT program. It is implemented by sampling the incident polar cosine of the source particle as follows: With μ defined as in Eq. 1 (above), then

$$\mu = \sqrt{\xi} \tag{2}$$

where ξ is a pseudo-random number uniformly distributed between 0 and 1. This is equivalent to sampling

$$\mu^2 = \xi \tag{3}$$

which then corresponds to the weighting of the sampled cosine, μ, by μ itself. It can be readily shown that for the weighting function $f(\mu) \equiv \mu$ the cosine-weighted source has, for a negatively or inward-directed normal, an average cosine given by

$$< \mu >= \frac{\int_{-1}^{0} \mu f(\mu) d\mu}{\int_{-1}^{0} f(\mu) d\mu} = -\frac{2}{3}, \tag{4}$$

and an average incident polar angle given by

$$< \theta >= \frac{\int_{-1}^{0} \cos^{-1} \mu f(\mu) d\mu}{\int_{-1}^{0} f(\mu) d\mu} = \frac{3\pi}{4}, \tag{5}$$

a necessary condition for uniform angular distribution (isotropic flux) with respect to the normal to the surface of impingence.

The cosine-weighted source option is coded into the original version of ITS/ACCEPT for source particles incident on a plane surface. To apply the cosine-weighted current source methodology to the dome geometry, we modified the dome source option that we had previously written for the ITS/ACCEPT code [8]. In Figure 5 we define the (x,y,z) axes to be the inertial reference frame for the standard velocity direction cosines (α, β, γ) as defined in ITS/ACCEPT, *i.e.* in terms of the polar and azimuthal angles θ and ϕ of the particle trajectory,

$$\begin{aligned} \alpha &= \sin\theta\cos\phi, \\ \beta &= \sin\theta\sin\phi, \\ \gamma &= \cos\theta. \end{aligned} \tag{6}$$

The primed coordinate system is defined by a rotation through angle Θ about the x-axis, as shown in Figure 5. The velocity direction cosines $(\alpha', \beta', \gamma')$ of the source electron in the primed system are correspondingly

$$\begin{aligned} \alpha' &= \sin\theta' \cos\phi', \\ \beta' &= \sin\theta' \sin\phi', \\ \gamma' &= \cos\theta'. \end{aligned} \tag{7}$$

The procedure to determine the orientation, expressed in the unprimed or inertial system, of the individual source electrons is as follows:

1) choose the point of particle incidence (x_o, y_o, z_o) to specify the rotation angle Θ by random uniform sampling on the hemispherical surface (Figure 5);
2) sample $\cos\theta' = -\sqrt{\xi}$, where as before, ξ is a pseudo-random number uniformly distributed between 0 and 1;
3) sample ϕ' uniformly on the interval $(0, 2\pi)$;
4) compute the direction cosines (α, β, γ) as

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\Theta & \sin\Theta \\ 0 & -\sin\Theta & \cos\Theta \end{bmatrix} \begin{bmatrix} \alpha' \\ \beta' \\ \gamma' \end{bmatrix}. \tag{8}$$

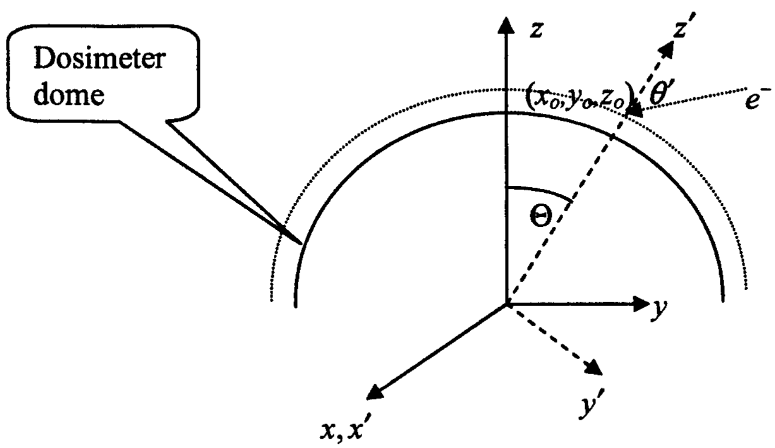

Figure 5. Angular orientation diagram for cosine-weighted source incident on CRRES dosimeter dome at (x_o, y_o, z_o). Θ is the angle of rotation about the x-axis. θ' is the polar angle between the source electron direction and the z' axis.

ITS/ACCEPT was modified (subroutine HIST) to perform the above source sampling procedure. The code modifications are shown in Appendix 1.

Two sets of 17 ITS/ACCEPT runs, 10^7 histories each, were made for the 17 source energies (see Table 1, column 1) listed in [1]. Comparisons of our results with [1]

are shown in Table 1. In our ITS/ACCEPT and MCNPX runs, the calculations of energy deposition were made using two methods: 1) the standard method of ACCEPT and MCNPX – (energy entering cell – energy exiting cell)[Table 1, columns 2,4,7]; and 2) summation over several energy bins, $\sum_i N(E_i)E_i$ where $N(E_i)$ is the pulse height in energy bin i and E_i is the average energy of the bin [Table 1, columns 3,5,6,8]. This second method was employed in [1], because the direct energy deposition calculation had apparently not been installed in the MCNP version available at the time (1993).

The first set of runs employed the source sampling procedure described above. A sample input file for ITS/ACCEPT is listed in Appendix 2. For comparison purposes, the runs in the second set were made for the same energies, but without cosine source weighting. The data shown in column 6 of Table 1 are the results given in [1] adjusted to correspond to the energy deposition units (MeV) produced by the ITS/ACCEPT and MCNPX calculations. In [1], the energy deposition results are given in units of MeV-cm^2-steradian per source electron, with the solid angle Ω factor for the CRRES_D1 geometry taken as 34.39 cm^2-steradian. The data of column 6 are the raw results given in [1] divided by this solid angle factor.

In Figure 6 we plot the silicon dosimeter (cell 1, Figure 3) flux response *vs.* source electron energy and dose response *vs.* source electron energy curves obtained with our calculations on the same graphs as the Ref. 1 data for comparison. The flux and dose response functions are defined as

$$\textit{Flux Response} = \Omega \sum_i N(E_i), \qquad \textit{Dose Response} = \Omega \sum_i E_i N(E_i),$$

with their respective units of cm^2-steradian and MeV-cm^2-steradian per source electron. The designations LOLET and HILET refer to the contributions to the response functions from electrons with energy below and above 1 MeV in the dosimeter (cell 1, Figure3), respectively.

Table 2 shows a comparison of ITS/ACCEPT and MCNPX energy deposition results in all cells (Figure 3) for the four source energies (2, 5, 10, 25 MeV) for which both programs were run.

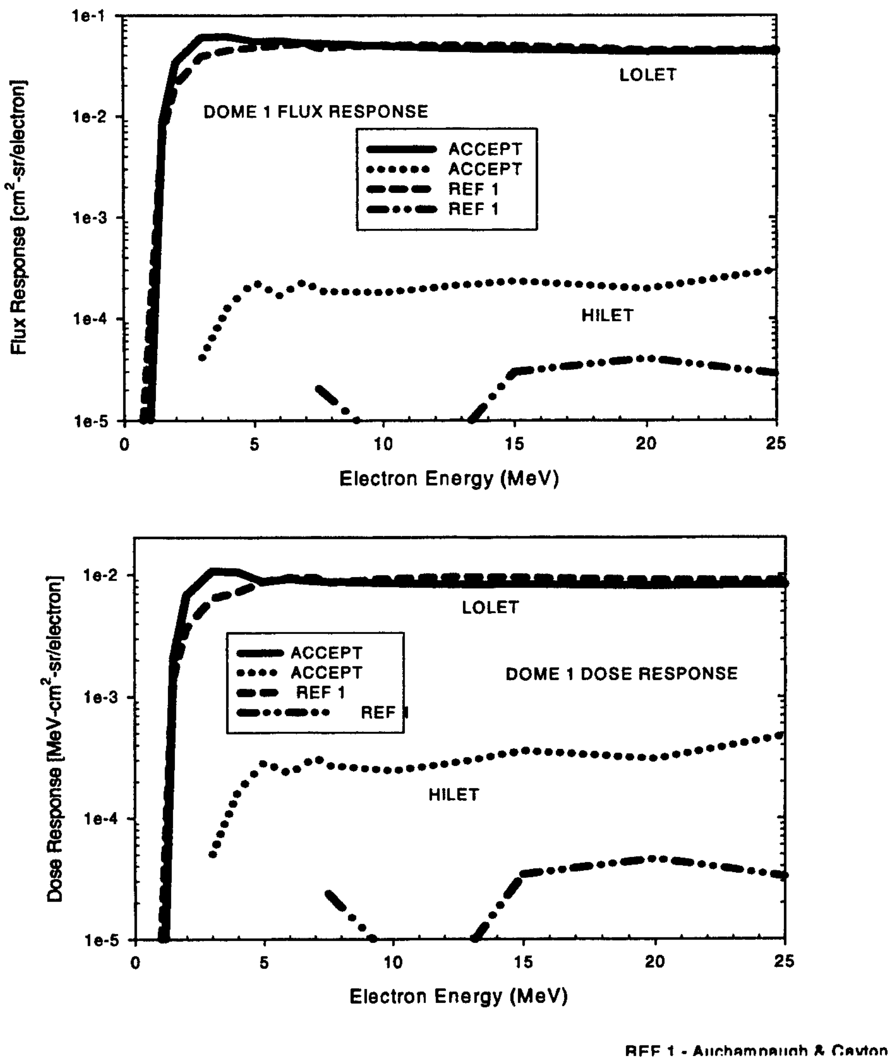

Figure 6. Comparison of Flux and Dose Response functions calculated with ITS/ACCEPT[5] and as reported in [1].

Table 2. Comparison of ITS/ACCEPT and MCNPX Energy Deposition (MeV) Calculations for CRRES_D1 Dosimeter (ALL CELLS, Figures 1,3) for Four Source Energies.

MCNPX CELL # (FIGURE 3)	SOURCE ENERGY = 2 MEV		SOURCE ENERGY = 5 MEV		SOURCE ENERGY = 10 MEV		SOURCE ENERGY = 25 MEV	
	ACCEPT	MCNPX	ACCEPT	MCNPX	ACCEPT	MCNPX	ACCEPT	MCNPX
1	1.975E-04	1.790E-04	2.668E-04	2.898E-04	2.380E-04	2.828E-04	2.215E-04	2.729E-04
2	6.491E-04	6.471E-04	9.164E-04	1.033E-03	7.997E-04	9.973E-04	7.458E-04	9.013E-04
5+6	1.308E+00	1.225E+00	1.875E+00	1.687E+00	2.124E+00	1.836E+00	2.205E+00	1.862E+00
10	6.332E-02	1.054E-01	1.908E-01	2.311E-01	1.943E-01	2.447E-01	1.732E-01	2.360E-01
9	4.008E-02	3.273E-02	8.126E-02	7.564E-02	6.787E-02	7.610E-02	6.147E-02	7.020E-02
11	1.204E-02	2.445E-02	8.851E-02	9.467E-02	8.759E-02	1.057E-01	7.540E-02	1.029E-01
17	6.120E-06	9.523E-03	2.737E-03	1.738E-02	1.665E-02	3.348E-02	1.342E-02	5.948E-02
16	4.050E-05	5.399E-03	1.559E-02	3.233E-02	6.323E-02	7.084E-02	1.204E-01	1.209E-01
15	3.602E-03	5.721E-03	2.902E-01	3.011E-01	1.530E+00	1.397E+00	4.161E+00	4.130E+00
12	2.292E-03	2.124E-03	4.812E-02	3.726E-02	3.963E-02	4.343E-02	3.353E-02	4.116E-02
13	7.183E-03	2.261E-02	1.440E-01	1.457E-01	1.450E-01	1.662E-01	1.216E-01	1.622E-01
14	1.394E-03	2.126E-02	4.484E-01	4.224E-01	4.907E-01	5.142E-01	3.895E-01	4.866E-01
TOTAL	1.439E+00	1.455E+00	3.186E+00	3.046E+00	4.760E+00	4.488E+00	7.355E+00	7.273E+00

2.2 HEP- Electron Transport Modeling

Extensive testing was performed on the ITS/ACCEPT input file written[9] for the HEP instrument. This file contains a complete, blueprint matching, geometry description for the in-flight model. It was felt that, due to the complicated geometry structure of the model, it would be advisable to run an extensive series of Monte Carlo calculations for model validation. To that end four sets, each consisting of ten source positions, of (50000 history) electron transport runs were made. The first of these consisted of pencil beam, 15 MeV, sources normally incident on the "top" (x = 5.0 cm) at ten uniformly distributed positions along z. The second and third sets were similarly distributed along z but were positioned on the side (y = 4.0 cm) and bottom (x = -3.0 cm). The fourth set consisted of calculations made with a 6-component energy (max. energy = 20 MeV) spectrum, point isotropic source embedded at ten uniformly spaced positions along the central (z) axis. In all cases run, there were no "lost particles" attributable to geometry specification errors.

3. PROTON TRANSPORT

3.1 CEASE – MCNPX Proton Transport Modeling

Two proton transport runs were made with the CEASE telescope model [10] for MCNPX, as requested by the Air Force sponsor, for 9 MeV proton flat disk sources, located at z = 0.457 cm on the telescope axis, at 40 degree slant incidence with respect to the z-axis. Partial listings of the run outputs are shown in Appendix 3. The geometry portions of these files, previously listed in [11] were omitted for brevity.

3.2 Grazing Angle Proton Scattering Calculations

An extensive series of proton transport calculations were made using MCNPX for protons beams incident on aluminum and iridium (6 × 5 × 1 cm) at shallow (grazing) angles of incidence (θ_{in} = 90.1, 90.5, 91.0°, ϕ = 90.0° as shown in Figure 7).

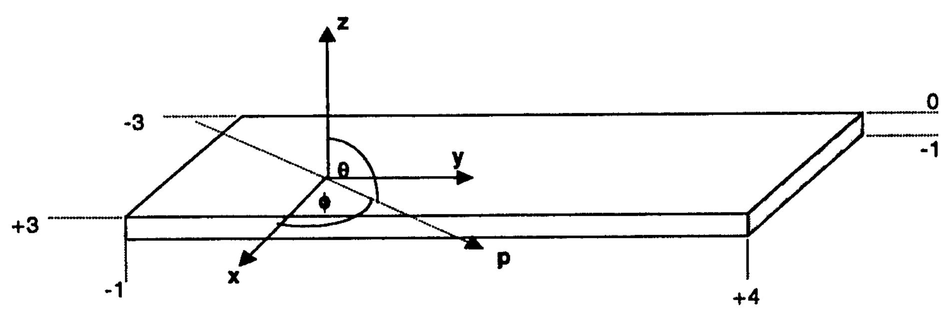

Figure 7. Problem geometry – proton beam incident on material slab

The motivation for this work was an investigation into the occurrence of unexpected radiation damage to one of the Chandra X-Ray Telescope cameras by grazing incidence protons. Standard Monte Carlo codes, such as Geant4[12], the program used to predict radiation damage in the Chandra, produced erroneous results. In our calculations we set out to investigate the treatment by standard Monte Carlo programs such as MCNPX of

the energy loss and relationship between the beam angle of incidence and the emergent angular distribution (from the top surface or vacuum interface of a material medium) for protons with grazing incident angles. To accomplish this, we ran MCNPX for 0.25 MeV protons incident on aluminum and 0.05, 0.25, 0.5, 1.0 MeV protons incident on iridium slabs at grazing angles. All of the Monte Carlo calculations were made using 10^8 case histories to ensure statistical reliability. High angular resolution emergent proton spectra were obtained, and plots made, for energy-angle, total energy, and azimuthal distributions.

The MCNPX proton transport results were analyzed from several aspects. Programs were written to convert the raw Monte Carlo data to histograms detailing:

(1) probability density $P_{E_{in}}\left(\left(\theta_{out}-90^\circ\right)\Big/\left(\theta_{in}-90^\circ\right);\ E_{out}\right)$ of emergent protons with exit polar angle θ_{out}, for every fixed incident angle θ_{in}, for every source energy E_{in} and exit energy bin width $\Delta E_{out} = 0.05E_{in}$. Representative plots of the probability density function for 0.25 MeV(=E_{in}) protons incident on iridium with incident angle 90.5 degrees(=θ_{in}), are shown in Figure 8. The five plots represent the emergent proton probability densities for the five emergent energy intervals 0-12.5, 12.5-25.0, 25.0-37.5, 37.5 50.0, 50.0-62.5 keV.

(2) emergent proton pulse-height distribution histogram plots $N(E_{out},\theta_{out};E_{in},\theta_{in})$; Representative plots are shown in Figures 9 and 10 for 0.25 MeV(=E_{in}) protons incident on iridium with incident angle 91.0 degrees(=θ_{in}). The emergent proton pulse-height distributions were calculated using 5 degree coarse resolution emergent angle(θ_{out}) bins in the range $0 \le \theta_{out} \prec 85^\circ$ (Figure 9) and 0.1 degree high resolution bins in the range $85^\circ \le \theta_{out} \le 90^\circ$ (Figure 10). The pulse-height distributions, expressed as the number of emergent protons per energy-angle bin, per incident proton, are normalized to unit proton incidence.

(3) emergent proton pulse-height energy spectra $N(E_{out};E_{in},\theta_{in})$ $[=\sum_{\theta_{out}} N(E_{out},\theta_{out};E_{in},\theta_{in})]$. The plot shown in Figure 11 is the pulse-height energy spectrum of emergent protons resulting from a 0.25 MeV proton beam incident on iridium with angle 91.0 degrees(=θ_{in}).

(4) emergent proton azimuthal (ϕ_{out}) distribution. The plot shown in Figure 12 is the distribution of ϕ_{out} for 0.5 MeV protons incident on iridium with θ_{in}= 91.0 degrees. The emergent azimuthal distribution is strongly peaked in the incident azimuthal direction, ϕ_{in}=90.0 degrees. This was found to be true for all 15 cases studied.

Additionally, plots were made for each incident energy-angle combination, of the maximum value of the probability density $P_{\max}(E_{out};E_{in},\theta_{in})$ (Figure 13) and its corresponding $\left.{}^{\theta_{out}}\!/\!_{\theta_{in}}\right|_{P_{\max}}$ ratio *vs.* E_{out} (Figure 14).

The results obtained with the MCNPX model do not exhibit specular, or near-specular, reflection[13] as may have been expected from experimental results [14,15]. Preliminary conclusions also reveal that the computed proton energy loss resulting from scatter of grazing incidence protons is an overestimation and are significantly larger than experimental observation [14,15]. In MCNPX and Geant4, proton energy loss calculations in the energy range studied are based on the assumption that the continuous slowing-down approximation applied in conjunction with the bulk material stopping power is appropriate. Pfandzelter *et al.*[15] have derived, from a study of the physics of surface potentials, expressions for the effective stopping power that applies in this situation.

Sample MCNPX output is shown in Appendix 4 for a 250 keV proton beam incident on iridium at 0.1° (θ_{in} = 90.1° as shown in Figure 7). The energy and angular bin structures of output emergent proton current tallies shown are as defined in items 1-3, above. For these investigations, a specialized source subroutine, listed in Appendix5, was written for MCNPX. The azimuthal (ϕ_{out}) distribution of the emergent proton current was extracted from PTRAC files produced in the MCNPX runs. A program (PHILOOK) was written to extract the azimuthal distribution data and convert them to the histogram form exemplified by the polar plot of Figure 12.

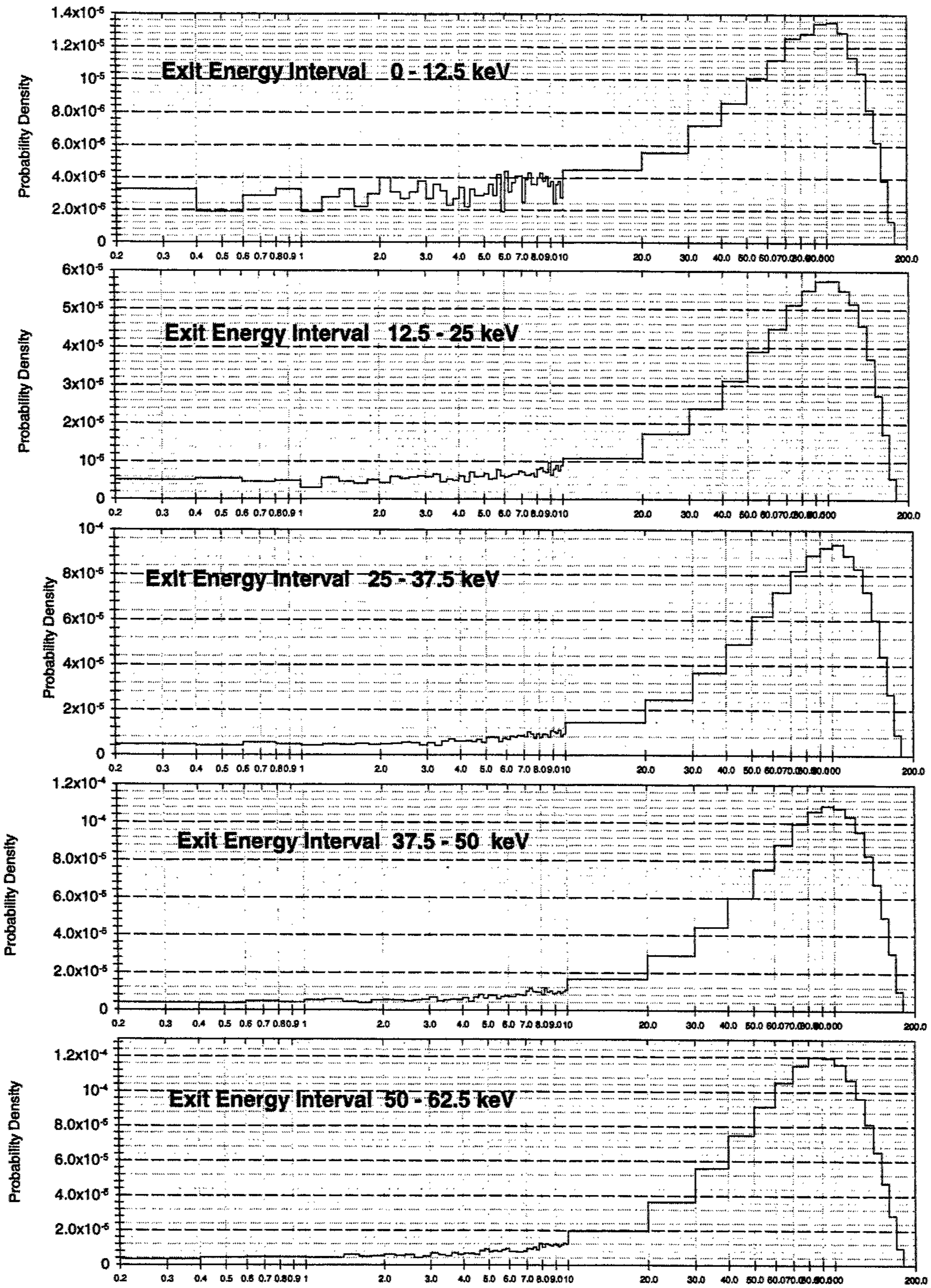

Figure 8. Sample plots of probability density $P_{E_{in}}\left(\left(\theta_{out}-90^\circ\right)\Big/\left(\theta_{in}-90^\circ\right);\ E_{out}\right)$ of emergent protons with exit polar angle θ_{out}, for incident angle θ_{in} = 90.5°, for source energy E_{in} = 250 keV and exit energy bins E_{out} = 0-12.5, 12.5-25.0, 25.0-37.5, 37.5 50.0, 50.0-62.5 keV.

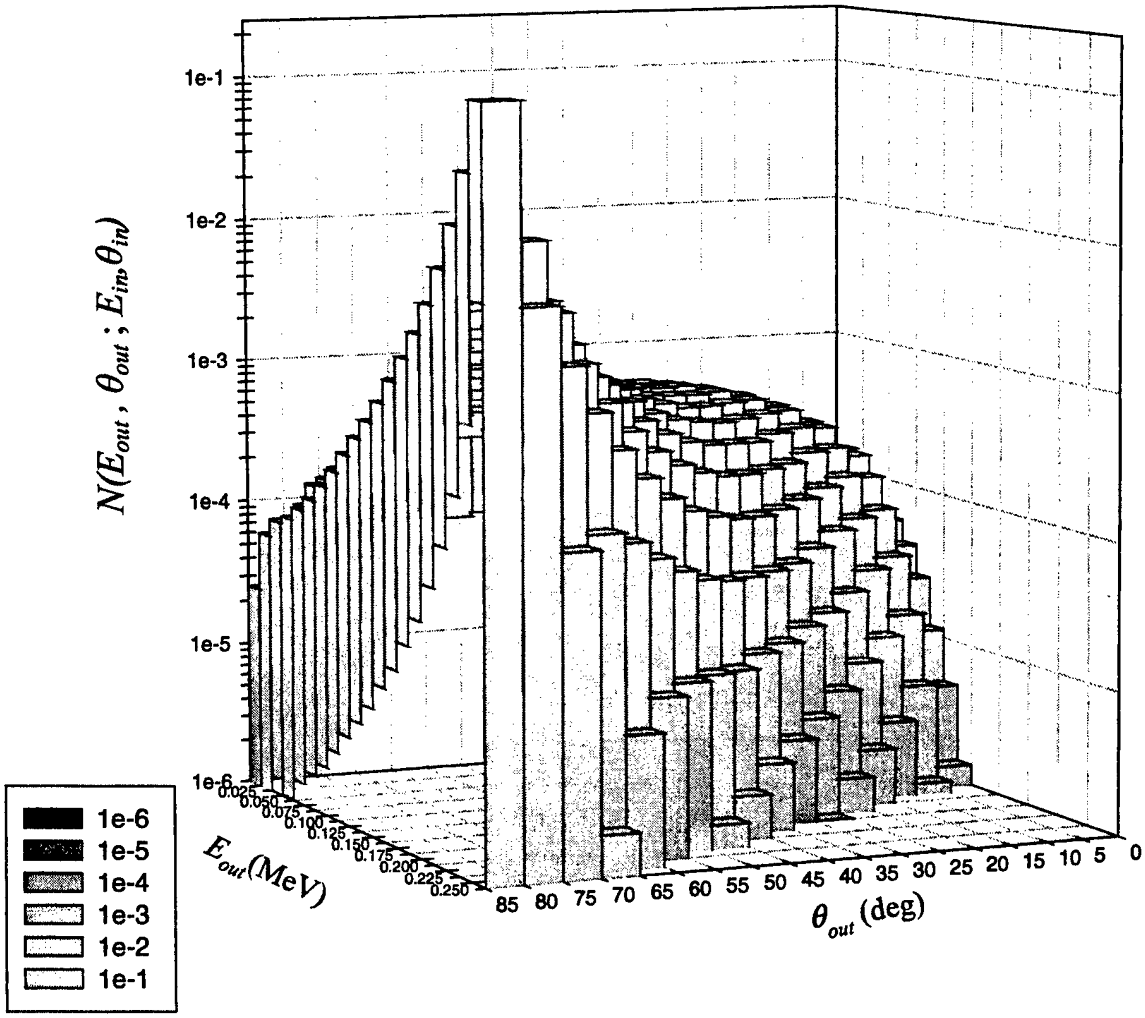

Figure 9. Emergent proton pulse-height distribution $N(E_{out}, \theta_{out}; E_{in}, \theta_{in})$ for 250 keV protons incident on Iridium slab at $\theta_{in} = 91.0^{\circ}$. Results are shown for $0 \leq \theta_{out} \prec 85^{\circ}$ in 5° increments.

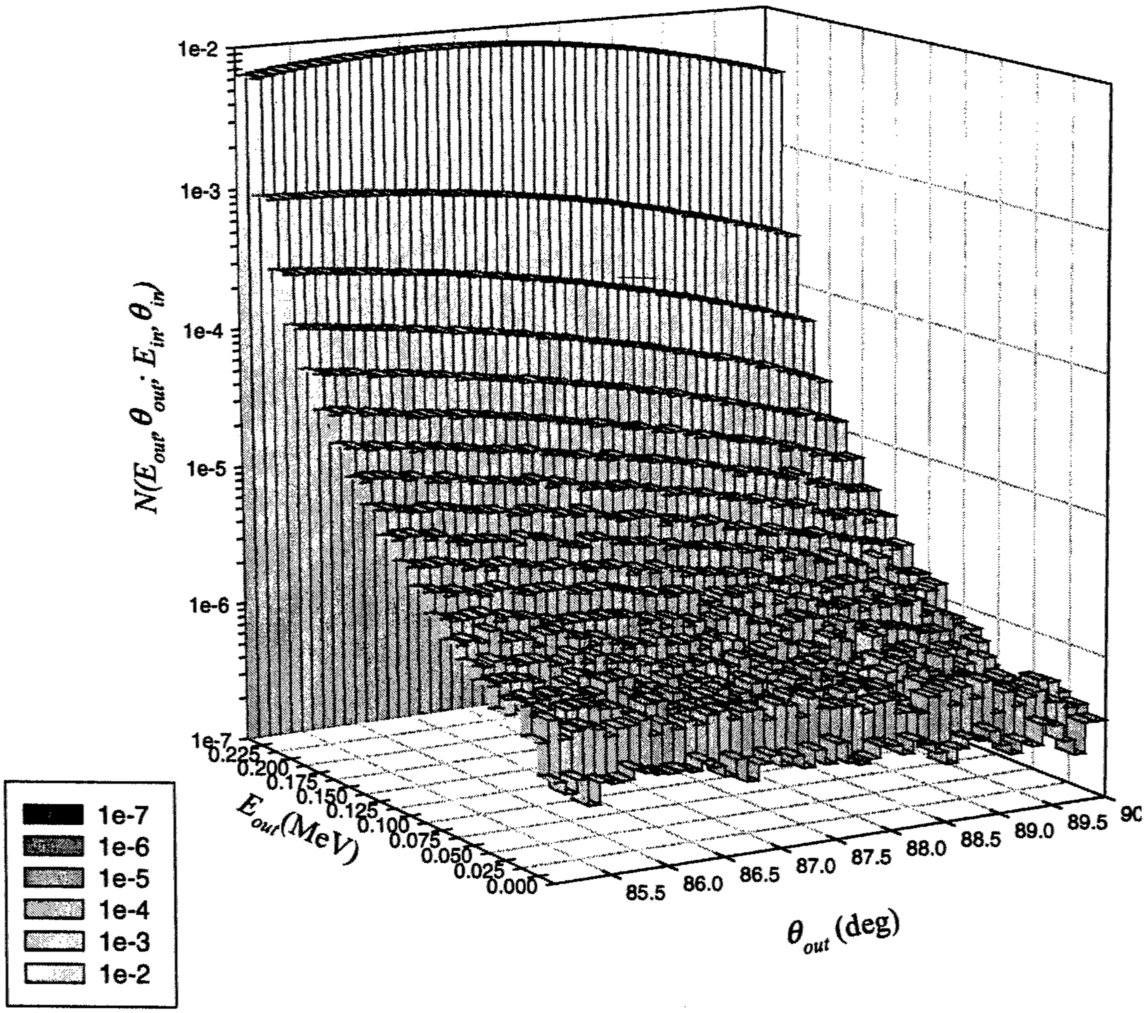

Figure 10. Emergent proton pulse-height distribution $N(E_{out}, \theta_{out}; E_{in}, \theta_{in})$ for 250 keV protons incident on Iridium slab at $\theta_{in} = 91.0^{\circ}$. Results are shown for $85^{\circ} \leq \theta_{out} \leq 90^{\circ}$ in 0.1° increments.

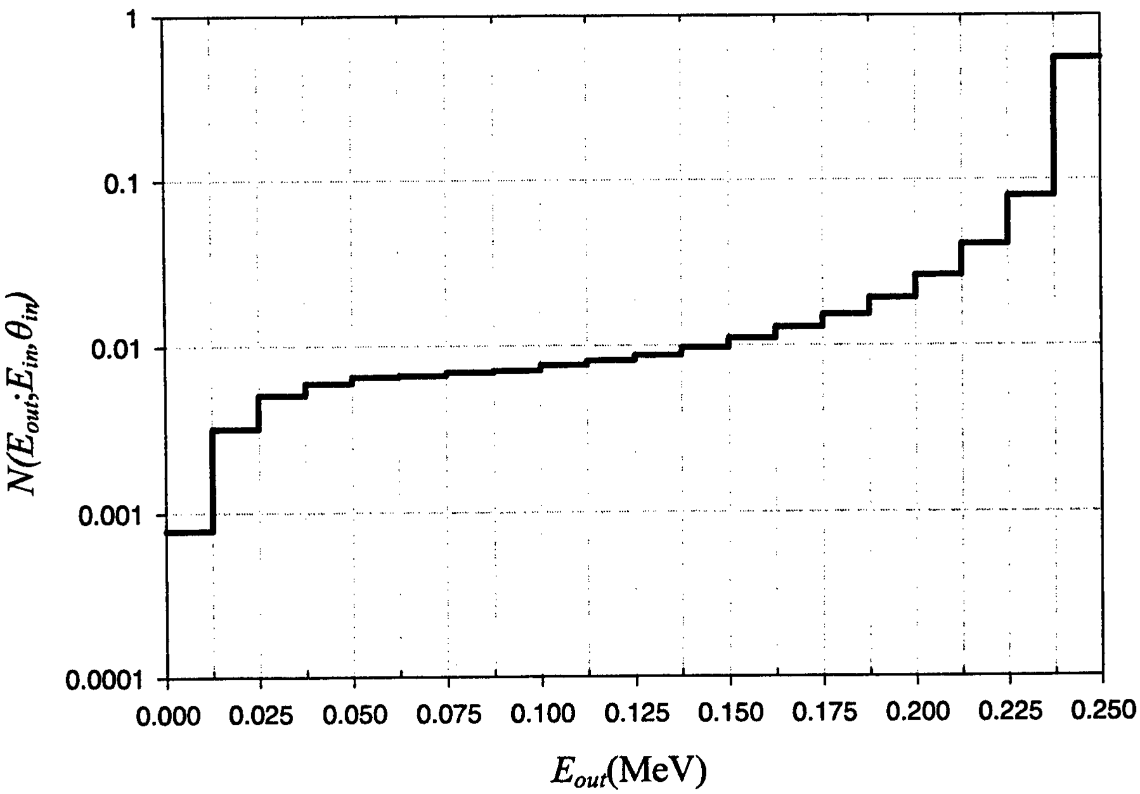

Figure 11. Pulse-height energy spectrum $N(E_{out};E_{in},\theta_{in})$ for protons emerging from iridium slab. E_{in}=250 keV, θ_{in}=90.5°.

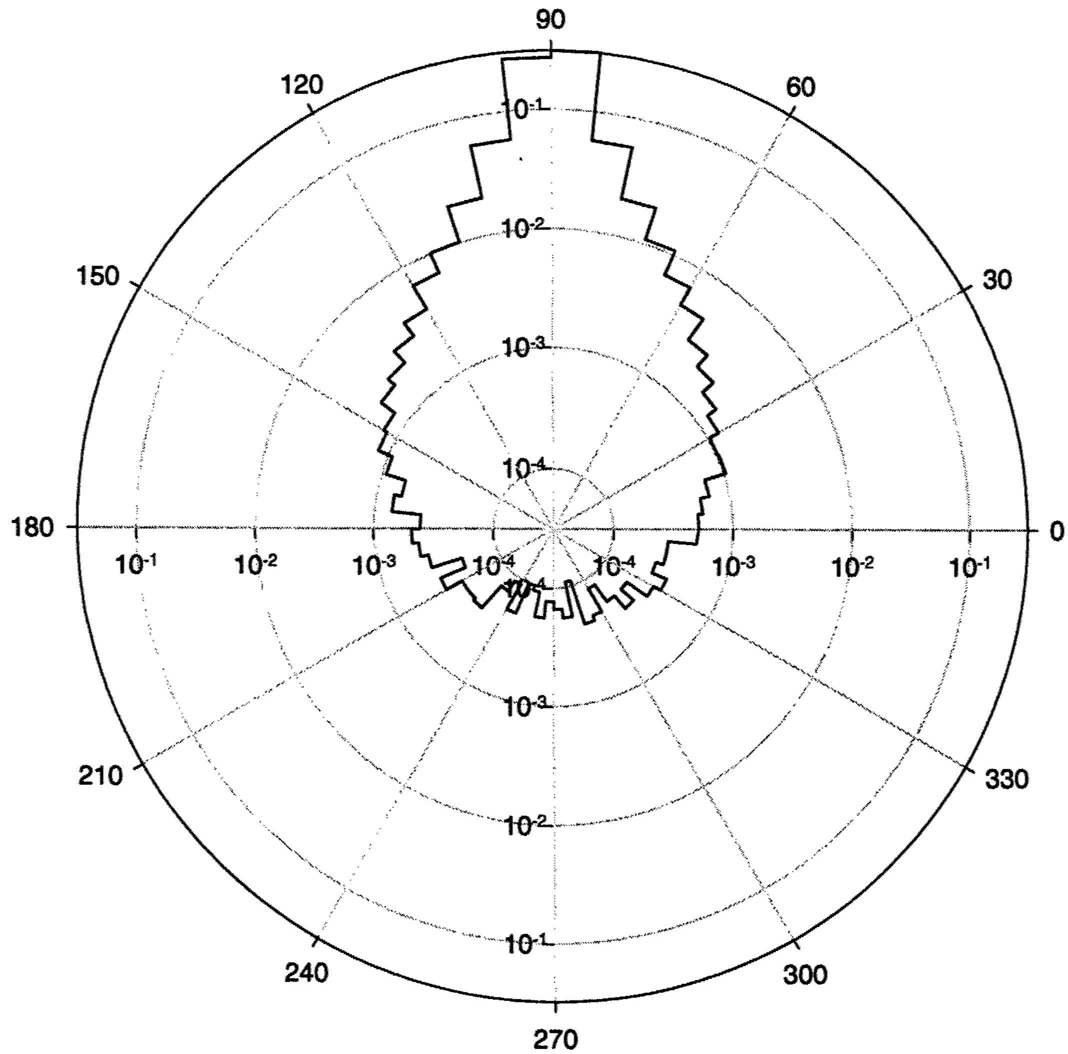

Figure 12. Emergent proton azimuthal (φ_{out}) distribution (normalized) from protons incident on iridium slab. φ_{in} = 90.0°; E_{in}=500 keV; θ_{in}= 91.0°.

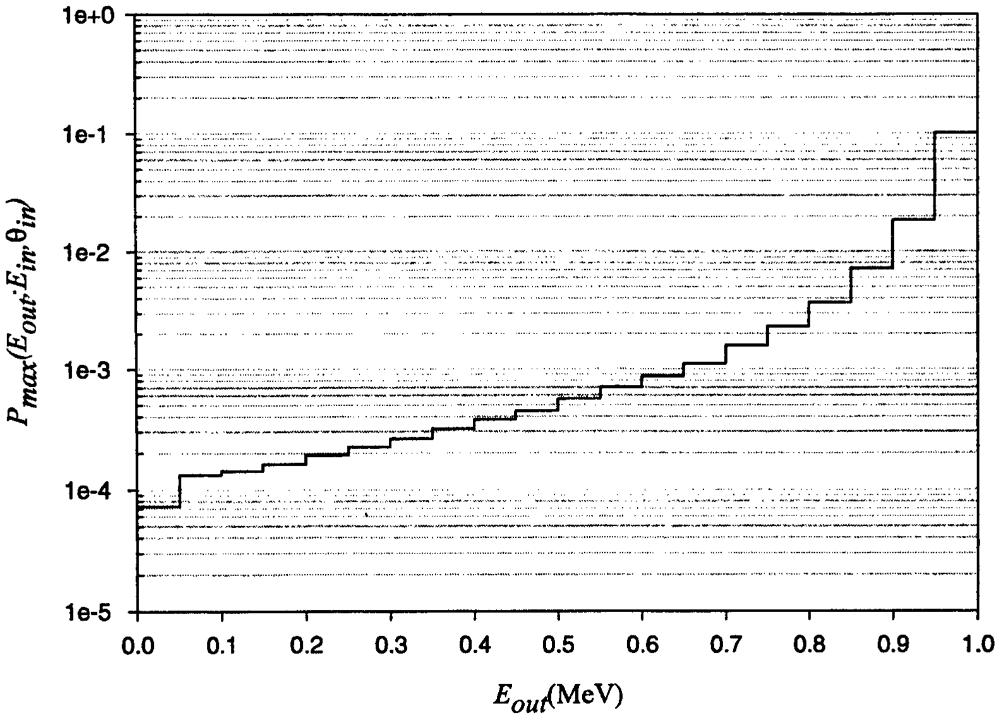

Figure 13. Maximum value of the probability density $P_{\max}(E_{out};E_{in},\theta_{in})$ $vs.E_{out}$ for protons of energy E_{in}=1.0 MeV incident on iridium at θ_{in} = 90.1°.

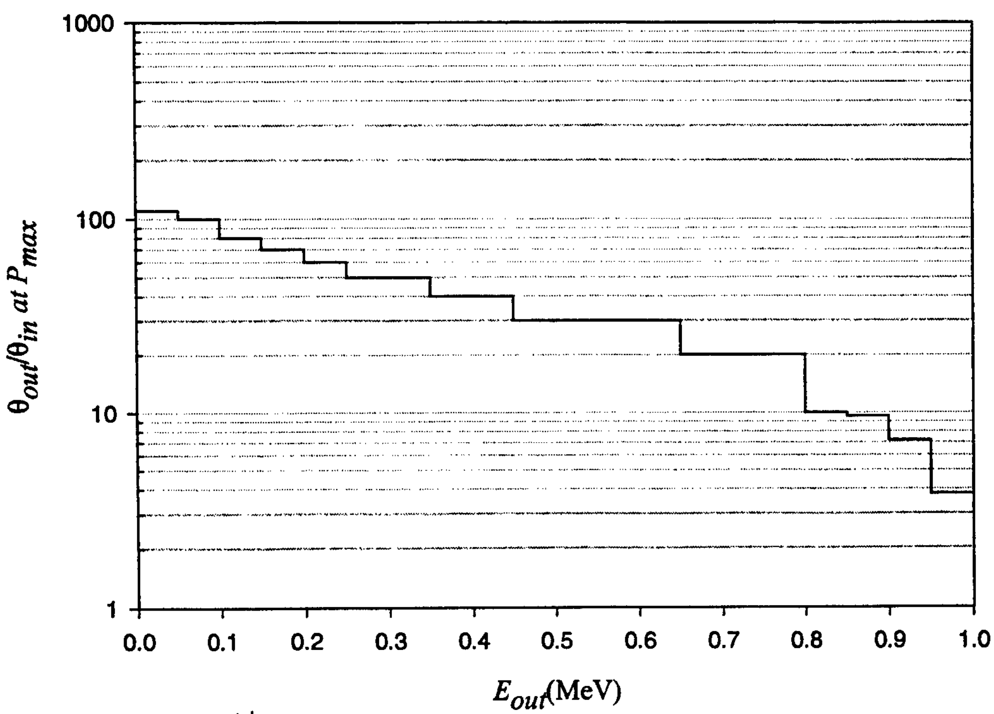

Figure 14. $\left.\theta_{out}/\theta_{in}\right|_{P_{\max}}$ $vs.E_{out}$ for protons of energy E_{in}=1.0 MeV incident on iridium at θ_{in} = 90.1°.

4. SUMMARY

During the period covered by this report, the technical activity and progress achieved consisted primarily of: 1) modeling and verification of earlier calculations of electron transport and energy deposition in CRRES dosimeters; 2) model validation of electron transport simulations in the HEP instrument; 3) modeling proton transport in the CEASE instrument; 4) the beginning of a study of the scattering of grazing incidence protons from material surfaces; and 5) providing computer code enhancements and advice on Monte Carlo simulation code implementation to AFRL.

References

1. Auchampaugh, G., Cayton, T., April 1993, *CRRES Dosimeter Simulations*, Los Alamos National Laboratory Report No. LA-12511-MS.
2. Briesmeister, J. F., Ed., September 1986, *MCNP – A General Monte Carlo Code for Neutron and Photon Transport*, Los Alamos National Laboratory Report LA-7396-M, Rev. 2.
3. Prael, R. E., Lichtenstein, H., September 1989, *User Guide to LCS: The LAHET Code System*, Los Alamos National Laboratory Report LA-UR-89-3014.
4. Waters, L. S., Ed., November 14,1999, *MCNPX™, Version 2.1.5 User's Manual*, Los Alamos Radiation Transport Group(X-6).
5. Halbleib, J. A. *et al., ITS - Integrated TIGER Series of Coupled Electron /Photon Monte Carlo Code System*,. ORNL RSICC Computer Code Package CCC-467.
6. Brautigam, D., May 15, 2002, AFRL/VSBXR, private communication.
7. Carter, L. L., Schwarz, R. A. *MCNP-VISED 26f- A Visual Editor for Creating MCNP4 Input Files*, ORNL RSICC Computer Code Package PSR-358.
8. Woolf, S., January 3, 2002, *Installation and Operation of Particle Transport Simulation Programs to Model the Detection and Measurement of Space Radiation by Space-borne Sensors*, ARCON Corp. Interim Scientific Report #2 (01 Aug. 2000 – 31 July 2001), Chapter 4, AFRL Contract #F19628-99-C-0077 (AD # not yet assigned).
9. Woolf, S., January 3, 2002, *Installation and Operation of Particle Transport Simulation Programs to Model the Detection and Measurement of Space Radiation by Space-borne Sensors*, ARCON Corp. Interim Scientific Report #2 (01 Aug. 2000 – 31 July 2001), Appendix 1, AFRL Contract #F19628-99-C-0077 (AD # not yet assigned).
10. B. Dichter, *et al.*, Compact Environmental Anomaly Sensor (CEASE): A Novel Spacecraft Instrument for *In Situ* Measurements of Environmental Conditions, *IEEE Trans. Nucl. Sci.* **45(6)**, 2758, Dec. 1998.
11. Woolf, S., December 29, 2000, *Installation and Operation of Particle Transport Simulation Programs to Model the Detection and Measurement of Space Radiation by Space-borne Sensors*, Air Force Research Laboratory Report, Appendix 3, AFRL –VS-TR-2001-1605, AD # 398366.
12. Geant4 Collaboration [Online]. http:///wwwinfo.cern.ch/asd/geant4/geant4.html
13. Firsov, O. B., 1967, *Reflection of fast ions from a dense medium at glancing angle*, Sov. Phys.- Doklady, vol. 11, No. 8, pp.732-733.
14. Winter, H., Wilke, M., Bergomaz, M., 1997, *Energy loss of fast protons in grazing scattering from an Al(111)-surface*, NIM B125, pp.124-127.
15. Pfandzelter, R., Stolzle, F., 1992, *Probing the stopping power near the surface by specular reflection of protons from graphite*, NIM B72, pp.163-175.

APPENDIX 1

Subroutine HIST for Cosine-Weighted Dome Source

```
      SUBROUTINE HIST                                                   HIST      00007
C ********************************************************************HIST      00009
C                                                                       HIST      00010
C     SUBROUTINE HIST IS CALLED BY                                      HIST      00011
C                                  ITS                                  HIST      00012
C     SUBROUTINE HIST CALLS                                             HIST      00013
C         INTRINSIC FUNCTIONS                                           HIST      00014
C                            SQRT, RANF                                 HIST      00015
C                            REAL              (CYLTRAN)                HIST      00016
C         EXTERNAL FUNCTIONS                                            HIST      00017
C                            CLASS, ECROS, EHIST, TIMER, PHIST          HIST      00018
C                            RANINT, RANSAV                             HIST      00019
C                            ZONE                         (CYLTRAN)     HIST      00020
C                            FOLD,   ZONEA                (ACCEPT)      HIST      00021
C                            PLTDAT                       (M-CODES)     HIST      00022
C                                                                       HIST      00023
C     ORIGINATION DATE      16 JAN 68.                                  HIST      00024
C     LAST MODIFIED         30 MAY 91                                   HIST      00025
C                                                                       HIST      00026
C     FUNCTION                                                          HIST      00027
C        THIS PROGRAM SAMPLES PHASE SPACE PARAMETERS FOR                HIST      00028
C        SOURCE PARTICLES.  SUBSEQUENTLY CALLS EITHER EHIST OR          HIST      00029
C        PHIST.  RETRIEVES "BANKED" ELECTRONS AND CALLS EHIST.          HIST      00030
C        TALLIES PULSE HEIGHT DISTRIBUTION.                             HIST      00031
C                                                                       HIST      00032
C ********************************************************************HIST      00033
C *** COMMON BLOCKS CNSTNT, PARAMS, OUT, CALC, XPED, STOR, STTS,        HIST      00034
C                  (PAREM)-ACCEPT                                       HIST      00035
C$    LIST(S=0)                                                         HIST      00036
CDIR$ NOLIST                                                            HIST      00037
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)                               CNSTNT    00081
      SAVE                                                              CNSTNT    00082
```

```
C                                                                       CNSTNT    00083
      PARAMETER (CT1M12 = 1.0D-12,  CT1EM8  = 1.0D-8, CT1EM7  = 1.0D-7) CNSTNT    00084
```

CNSTNT common block is identical to that given in Reference 3 – listing omitted for brevity.

```
      PARAMETER (CCOHLM=57.031547D0,     CCOHMX=80.654788D0)            CNSTNT    00140
C                                                                       PARAMS    00002
C ----------------------------------------------------------------------PARAMS    00003
```

PARAMS common block is identical to that given in Appendix 2, Reference 4.

```
C --------------------------------------------------                    PARAMS    00086
      PARAMETER (NLAST = 50)                                            PARAMS    00089
      PARAMETER ( INUMK = 3,   INGP = INMT)                             PARAMS    00103
         COMMON /EXTSORC/ IRECTS,IDISKS,XLOWS,XHIGHS,YLOWS,YHIGHS,ZLOWS,
     $   ZHIGHS,XCENT,YCENT,ZCENT,XCIR,YCIR,ZCIR,KPERPYZ,KPREPXZ,KPERPXY,
     $   IDOME,RDOME
      LOGICAL RRKILL, FLMTEL                                            OUT       00002
      COMMON /OUT/                                                      OUT       00003
```

```
      1 FLMTEL(INGP)                                                    OUT      00004
```

OUT common block is identical to that given in Reference 3 – listing omitted for brevity.

```
      $         FLESCP, FLNOK, FLNEL, FLBAD, FLINIT, FLGSEC             OUT      00095
C                                                                       CALC     00002
       COMMON /CALC/                                                    CALC     00003
      1                                                                          )4
```

CALC common block is identical to that given in Reference 3 – listing omitted for brevity.

```
C                                                                       CALC     00139
C                                                                       XPED     00002
       COMMON /XPED/                                                    XPED     00003
      1 DETOUR(INMT), RHO(INMT), MT, MTP, MTP0                          XPED     00010
C                                                                       XPED     00012
       LOGICAL DMPFLG, FLMC                                             STTS     00002
       DOUBLE PRECISION IRSAV                                           STTS     00010
       COMMON  /STTS/  IB,  NB,  NSORS, IBT, BOLD, BATCH, KPUTMX, DMPFLG STTS    00017
      $ ,  IHIST,   IRSAV,  KPUT, FLMC                                  STTS     00018
C                                                                       STTS     00019
C                                                                       PAREM    00002
       CHARACTER*3 OTYPE(10), OBODY                                     PAREM    00003
       LOGICAL FLDBG, FLDBGL                                            PAREM    00004
       COMMON /PAREM/                                                   PAREM    00008
      $  XB(3),    WT(3),    RIN,   ROUT,   PINF,   DIST,   IR,         PAREM    00009
      $  FLDBG,    IRPRIM,   ICALL, LSURF,  NBO,    LRI,    LRO,        PAREM    00013
      $  KLOOP,    LOOP,     ITYPE, FLDBGL                              PAREM    00014
       COMMON /PAREMO/  OTYPE                                           PAREM    00015
C                                                                       PAREM    00016
          COMMON /HITS/EDPR(10),EDNK(10),EDSC(10),EDTL(10),LHCL(10),NINDV,
      $  IHSTRY,COFSRC(6,25,10),COFLEGY(6,25),COFLEG(6)

C$     LIST(S=1)                                                        HIST     00047
CDIR$ LIST                                                              HIST     00048
       COMMON /STOR/                                                    STOR     00002
      1 CTHS(NLAST),  TS(NLAST),  WS(NLAST),  ZS(NLAST),  IPRS(NLAST),  STOR     00003
      2 LBS(NLAST),   NTS(NLAST)                                        STOR     00004
      $ ,XS(NLAST),   YS(NLAST),  STHS(NLAST),                          STOR     00006
      3 CPHS(NLAST),  SPHS(NLAST)                                       STOR     00007
      4 ,LBCS(NLAST)                                                    STOR     00009
C                                                                       HIST     00050
       EXTERNAL RAN                                                     RANNUM   00003
C                                                                       HIST     00089
       CIMAX = IMAX                                                     HIST     00090
       IF (FLSPEC) THEN                                                 HIST     00091
         TAV = CZERO                                                    HIST     00092
       ELSE                                                             HIST     00093
         TAV = CIMAX*TIN                                                HIST     00094
       END IF                                                           HIST     00095
C     ___________________                                               HIST     00096
       CALL RANINT(IRA)                                                 HIST     00097
C     -------------------                                               HIST     00098
       IF (IB .EQ. 1) INRAN = IRA                                       HIST     00101
       DO 130 I = 1, IMAX                                               HIST     00103
         IHSTRY=I
             DO 1301 JJJ=1,10
                 EDPR(JJJ)=0.
                 EDNK(JJJ)=0.
                 EDSC(JJJ)=0.
 1301      EDTL(JJJ)=0.
           IHIST = I                                                    HIST     00104
       MODTMJ = MIN(10000,IMAX)                                         LAHEY    00017
       IF(I.EQ.MODTMJ*(I/MODTMJ)) THEN                                  LAHEY    00018
```

```
      CALL TOTTIM(XTMJ)                                                 LAHEY    00019
      WRITE(*,'(/'' HISTORY'',I8,'', ELAPSED MINUTES'',F10.2)')         LAHEY    00020
     1I,XTMJ/60.                                                        LAHEY    00021
      ENDIF                                                             LAHEY    00022
        W      = CONE                                                   HIST     00105
        CWCF   = W                                                      HIST     00106
        LAST   = 0                                                      HIST     00107
C      ____________________                                             HIST     00108
        CALL RANSAV(IRSAV)                                              HIST     00109
C      --------------------                                             HIST     00110
C                                                                       HIST     00111
C __________________                                                    HIST     00112
C ... SOURCE ENERGY                                                     HIST     00113
C ------------------                                                    HIST     00114
        IF (FLSPEC) THEN                                                HIST     00115
          RA = RAN(IRAN)                                                HIST     00116
          DO 14 JHIST = 2,JSPEC                                         HIST     00117
             IF ( RA. GT. SPECIN(JHIST) ) GO TO 16                      HIST     00118
   14     CONTINUE                                                      HIST     00119
   16     T = ESP(JHIST-1) + ( RA -SPECIN(JHIST-1) )*( ESP(JHIST)       HIST     00120
     $      - ESP(JHIST-1) )/( SPECIN(JHIST) - SPECIN(JHIST-1) )        HIST     00121
          TAV = TAV + T                                                 HIST     00122
          IF ( (FLESRC .AND. (T .GT. TCUT )) .OR.                       HIST     00123
     $         (.NOT. FLESRC .AND. (T .GT. TPCUT)) ) THEN               HIST     00124
              GO TO 20                                                  HIST     00125
          ELSE                                                          HIST     00126
              NTREJ = NTREJ + 1                                         HIST     00127
              TREJ  = TREJ + W*T                                        HIST     00128
              GO TO 1299                                                HIST     00129
          END IF                                                        HIST     00130
        END IF                                                          HIST     00131
        T  = TIN                                                        HIST     00132
   20   NT = NTFST                                                      HIST     00133
C      ____________________                                             HIST     00134
        CALL CLASS (T,NT)                                               HIST     00135
C      --------------------                                             HIST     00136
      IF(IDOME.EQ.0)THEN
C ____________________                                                  HIST     00137
C ... SOURCE DIRECTION                                                  HIST     00138
C ---------------------                                                 HIST     00139
        IF (ICTH .EQ. 2) THEN                                           HIST     00140
          RA  = RAN(IRAN)                                               HIST     00141
          COM = CTHIN+ RA*(CONE-CTHIN)                                  HIST     00142
        ELSE IF (ICTH .EQ. 3) THEN                                      HIST     00143
          RA  = RAN(IRAN)                                               HIST     00144
          COM = SQRT(CTHIN+RA*(CONE-CTHIN))                             HIST     00145
        ELSE IF (ICTH .EQ. 1) THEN                                      HIST     00146
          CTH(1) = CTSR                                                 HIST     00147
          STH(1) = STSR                                                 HIST     00149
          CPH(1) = CPSR                                                 HIST     00150
          SPH(1) = SPSR                                                 HIST     00151
          GO TO 69                                                      HIST     00153
        END IF                                                          HIST     00154
C                                                                       HIST     00155
        IF (CTSR .EQ. CONE) THEN                                        HIST     00156
          CTH(1) = COM                                                  HIST     00157
          STH(1) = SQRT(CONE-COM*COM)                                   HIST     00159
          RA     = RAN(IRAN)                                            HIST     00160
          JAZ    = RA*C360                                              HIST     00161
          CPH(1) = CCH(JAZ+1)                                           HIST     00162
          SPH(1) = SCH(JAZ+1)                                           HIST     00163
        ELSE                                                            HIST     00165
C         ______________________________________________________________HIST     00172
          CALL FOLD(CTSR,STSR,CPSR,SPSR,COM,CTH(1),STH(1),CPH(1),SPH(1))HIST     00173
C         --------------------------------------------------------------HIST     00174
        END IF                                                          HIST     00176
        END IF
C ____________________                                                  HIST     00177
```

```
C ... SOURCE POSITION                                                  HIST      00178
C --------------------                                                 HIST      00179
 69      IF (SORCIN .NE. CZERO) THEN                                   HIST      00198
           RA    = RAN(IRAN)                                           HIST      00199
           R     = SQRT(RA)*SORCIN                                     HIST      00200
           RA    = RAN(IRAN)                                           HIST      00201
           JAZ   = RA*C360                                             HIST      00202
           SCHR = SCH(JAZ+1)*R                                         HIST      00203
           CCHR = CCH(JAZ+1)*R                                         HIST      00204
            IF (IDISKS .EQ. 0) THEN
                 X     = XSR + CCHR*W1X+SCHR*W2X
                 Y     = YSR+CCHR*W1Y+SCHR*W2Y
                 Z     = ZSR+CCHR*W1Z+SCHR*W2Z
               ELSE
                  IF(KPERPXY.EQ.1)THEN
                     X = XCENT + CCHR
                        Y = YCENT + SCHR
                        Z = ZCENT
                      END IF
                      IF (KPERPXZ.EQ.1)THEN
                        X = XCENT + CCHR
                        Y = YCENT
                        Z = ZCENT + SCHR
                      END IF
                      IF(KPERPYZ.EQ.1)THEN

                 X = XCENT
                        Y = YCENT + CCHR

                 Z = ZCENT + SCHR

               END IF

            END IF

         ELSE

            IF (IRECTS .EQ. 0 .AND. IDOME.EQ.0)THEN                     HIST      00208
           X = XSR                                                     HIST      00209
           Y = YSR                                                     HIST      00210
           Z = ZSR                                                     HIST      00211
            ELSE
                 IF(IRECTS.NE.0)THEN

               RRAA1 = RAN(IRAN)

               RRAA2 = RAN(IRAN)

               IF (KPERPXY .EQ. 1) THEN

                 X = XLOWS + RRAA1*(XHIGHS-XLOWS)
                 Y = YLOWS + RRAA2*(YHIGHS-YLOWS)
                 Z = ZLOWS

               END IF

               IF (KPERPXZ. EQ. 1) THEN

                 X = XLOWS + RRAA1*(XHIGHS-XLOWS)
                 Y = YLOWS

                 Z = ZLOWS + RRAA2*(ZHIGHS-ZLOWS)
               END IF

               IF (KPERPYZ .EQ.1) THEN

                 X = XLOWS
```

New Code

```
                 Y = YLOWS + RRAA1*(YHIGHS-YLOWS)
                 Z = ZLOWS + RRAA2*(ZHIGHS-ZLOWS)
               END IF
                 END IF
C     DOME SOURCE
                 IF(IDOME.NE.0)THEN
                 STHDM=RAN(IRAN)
             CTHDM=SQRT(1.-STHDM*STHDM)
             PPHDM=C2PI*RAN(IRAN)
             CPPHDM=COS(PPHDM)
             SPPHDM=SIN(PPHDM)
             ALDM=STHDM*CPPHDM
             BTDM=STHDM*SPPHDM
             X=RDOME*ALDM
             Y=RDOME*BTDM
             Z=RDOME*CTHDM
  106             PHSDM=C2PI*RAN(IRAN)
C        COSINE-WEIGHTED SOURCE
             CTHSDM=-SQRT(RAN(IRAN))
             STHSDM=SQRT(1.-CTHSDM*CTHSDM)
             SPHSDM=SIN(PHSDM)
             CPHSDM=COS(PHSDM)
             UUUD=STHSDM*CPHSDM
             VVVD=STHSDM*SPHSDM
             WWWD=CTHSDM
             AAAD=SQRT(UUUD**2+VVVD**2+WWWD**2)
             UUUD=UUUD/AAAD
             VVVD=VVVD/AAAD
             WWWD=WWWD/AAAD
        ALPDD=UUUD
        BETDD=VVVD*CTHDM+WWWD*STHDM
        GAMDD=-VVVD*STHDM+WWWD*CTHDM
             PRODD=ALDM*ALPDD+BTDM*BETDD+CTHDM*GAMDD
             IF(PRODD.GT.0.0)GO TO 106
             STH(1)=SQRT(1.-GAMDD**2)
             CTH(1)=GAMDD
        IF(STH(1).LT.1.E-6)GO TO 106
             SPH(1)=BETDD/STH(1)
             CPH(1)=ALPDD/STH(1)
             END IF
           END IF

        END IF                                                    HIST  00212
C                                                                 HIST  00213
        XB(1) = X                                                 HIST  00220
        XB(2) = Y                                                 HIST  00221
        XB(3) = Z                                                 HIST  00222
        WT(1) = STH(1)*CPH(1)                                     HIST  00223
        WT(2) = STH(1)*SPH(1)                                     HIST  00224
        WT(3) = CTH(1)                                            HIST  00225
C       ____________                                              HIST  00226
        CALL ZONEA                                                HIST  00227
C       ------------                                              HIST  00228
        LB   = IR                                                 HIST  00229
        LBCZ = IRPRIM                                             HIST  00230
        IPR = 1                                                   HIST  00232
C                                                                 HIST  00233
C ___________________________                                     HIST  00234
C ... CALL TRACKING ROUTINES                                      HIST  00235
C ---------------------------                                     HIST  00236
   70   IF ( FLESRC .OR. (IPR .NE. 1) ) THEN                      HIST  00237
C         ______________________________________                  HIST  00238
C ...     PARTICLE TO BE TRACKED IS AN ELECTRON                   HIST  00239
C         --------------------------------------                  HIST  00240
          IF (MT .NE. MAT(LB)) THEN                               HIST  00241
            MT = MAT(LB)                                          HIST  00242
          END IF                                                  HIST  00248
C           ____________                                          HIST  00249
            CALL EHIST                                            HIST  00250
C           ------------                                          HIST  00251
        ELSE                                                      HIST  00252
C         _____________________________________                   HIST  00253
C   ...   PARTICLE TO BE TRACKED IS A PHOTON                      HIST  00254
C         -------------------------------------                   HIST  00255
          LPCZ = LBCZ                                             HIST  00262
C         ______________________________________________________  HIST  00265
          CALL PHIST(X,Y,Z,LB,CTH(1),STH(1),CPH(1),SPH(1),T,W,1)  HIST  00266
C         ------------------------------------------------------  HIST  00267
        END IF                                                    HIST  00269
C                                                                 HIST  00270
C ______________________________________________________________  HIST  00271
```

```
C ... REMOVE SECONDARY ELECTRONS FROM STORAGE FOR TRANSPORT          HIST     00272
C -----------------------------------------------------------         HIST     00273
        IF (LAST .NE. 0) THEN                                         HIST     00274
          LB      = LBS(LAST)                                         HIST     00275
          Z       = ZS(LAST)                                          HIST     00276
          T       = TS(LAST)                                          HIST     00277
          NT      = NTS(LAST)                                         HIST     00278
          CTH(1)  = CTHS(LAST)                                        HIST     00279
          W       = WS(LAST)                                          HIST     00280
          IPR     = IPRS(LAST)                                        HIST     00281
C                                                                     HIST     00283
          X       = XS(LAST)                                          HIST     00284
          Y       = YS(LAST)                                          HIST     00285
          STH(1)  = STHS(LAST)                                        HIST     00286
          CPH(1)  = CPHS(LAST)                                        HIST     00287
          SPH(1)  = SPHS(LAST)                                        HIST     00288
C                                                                     HIST     00289
          LBCZ  = LBCS(LAST)                                          HIST     00291
          KLOOP = KLOOP+1                                             HIST     00292
          LAST = LAST-1                                               HIST     00294
          GO TO 70                                                    HIST     00295
        END IF                                                        HIST     00296
C                                                                     HIST     00297
        IF (.NOT. FLPHD) GO TO 1299                                   HIST     00298
C                                                                     HIST     00299
C ____________________________________                                HIST     00300
C ... SCORE PULSE-HEIGHT DISTRIBUTION                                 HIST     00301
C -----------------------------------                                 HIST     00302
        EABST = CZERO                                                 HIST     00303
        DO 100 LS=LPHDB,LPHDE                                         HIST     00304
          EABST     =   EABST+PHDD(LS)                                HIST     00305
  100     PHDD(LS) = CZERO                                            HIST     00306
        DO 110 JS=1,JSMAX                                             HIST     00307
          IF(SMARK(JS) .LE. EABST) GO TO 120                          HIST     00308
  110   CONTINUE                                                      HIST     00309
        NPHD = NPHD+1                                                 HIST     00310
        GO TO 1299                                                    HIST     00311
  120   ABE(JS) = ABE(JS)+CWCF                                        HIST     00312
 1299   IF(NINDV.EQ.0)GO TO 130
        DO 1298 NIND=1,NINDV
         EDTL(NIND)=EDPR(NIND)+EDNK(NIND)+EDSC(NIND)
1298  CONTINUE
          WRITE(44)(EDPR(NIND),EDNK(NIND),EDSC(NIND),EDTL(NIND),NIND
     $  =1,NINDV)
          130 CONTINUE                                                   HIST     00313
C    _________________                                                HIST     00314
      CALL RANSAV(IRC)                                                HIST     00315
C    ------------------                                               HIST     00316
      RETURN                                                          HIST     00317
      END                                                             HIST     00318
```

APPENDIX 2
CRRES_D1 Sample Input File for ACCEPT Run

```
TITLE
  15 MEV DOME SOURCE on CRRES DOME 1
********************** GEOMETRY ***********************
GEOMETRY
*1
  RCC    0.0    0.0    0.0    0.0         0.00000  0.04030   .05093
*2
  RCC    0.0    0.0    -0.07620  0.0     .00000  0.07620   .06350
*3
  RPP    -.09525  .09525  -.09525  .09525  .00000  0.04030
*4
  RCC    0.0    0.0    -0.07620  0.0     .00000  0.07620   0.5080
*5
  RCC    0.0    0.0    -0.07620  0.0     .00000  0.07620   1.22936
*6
  RCC    0.0    0.0    -0.07620  0.0     .00000  0.07620   1.46812
*7
  RCC    0.0    0.0    -0.10668  0.0     .00000  0.03048   0.32385
*8
  RCC    0.0    0.0    -0.10668  0.0     .00000  0.03048   1.22936
*9
  RCC    0.0    0.0    -0.10668  0.0     .00000  0.03048   1.46812
*10
  RCC    0.0    0.0    -0.15748  0.0     .00000  0.05080   0.32385
*11
  RCC    0.0    0.0    -0.15748  0.0     .00000  0.05080   1.22936
*12
  RCC    0.0    0.0    -0.15748  0.0     .00000  0.05080   1.46812
*13
  RCC    0.0    0.0    -0.31496  0.0     .00000  0.15748   1.22936
*14
  RCC    0.0    0.0    -0.31496  0.0     .00000  0.15748   1.46812
*15
  RCC    0.0    0.0    -0.94996  0.0     .00000  0.635     1.11125
*16
  RCC    0.0    0.0    -0.94996  0.0     .00000  0.635     1.22936
*17
  RCC    0.0    0.0    -0.94996  0.0     .00000  0.635     1.46812
*18
  RCC    0.0    0.0    -1.58496  0.0     .00000  0.635     1.11125
*19
  RCC    0.0    0.0    -1.58496  0.0     .00000  0.635     1.22936
*20
  RCC    0.0    0.0    -1.58496  0.0     .00000  0.635     1.46812
*21
  RCC    0.0    0.0     0.0      0.0     .00000  1.01981   1.01981
*22
  RCC    0.0    0.0     0.0      0.0     .00000  1.22936   1.22936
*23
  RCC    0.0    0.0     0.0      0.0     .00000  1.46812   1.46812
*24
  SPH    0.0    0.0    0.0  1.01981
*25
  SPH    0.0    0.0    0.0  1.22936
*26
  SPH    0.0    0.0    0.0  1.46812
*27
  RCC    0.0    0.0    -2.58496   0.0    0.0    1.0   1.46812
*28
  SPH    0.0    0.0    0.0  1.005
*29
  RCC    0.0   0.0   0.0   0.0   0.0   1.005   1.005
*30
  SPH    0.0    0.0   0.0   5.0
*31
  SPH    0.0    0.0    0.0        10.0
```

```
  END
*SI
  Z01 +1
  Z02 +3 -1
*VOID
  Z03 +29 +28 -1 -3
*AL
  Z04 +25 -24 +22
  Z05 +5 -4 -2
*VOID
  z06 +6 -5 -4 -2
*AL2O3
  Z07 +4 -2
*VOID
  Z08 +2
*AL
  Z09 +8 -7
*VOID
  z10 +9 -8 -7
  Z11 +7
  z12 +12 -11 -10
*AL
  Z13 +11 -10
*NI
  Z14 +10
*AL
  Z15 +13
*VOID
  z16 +14 -13
  z17 +17 -16
*AL
  z18 +16 -15
  z19 +19 -18
*W-Fe
  Z20 +15
  z21 +18
*AL
  z22 +20 -19
*VOID
  Z23 +24 -28 +21
  Z24 +23 -25 +26
  z25 +23 -26
  Z26 +27
  Z27 +29 -1 -2 -3 -4 -5 -6 -7 -8 -9 -10 -11 -12 -13 -14 -15
          -16 -17 -18 -19 -20 -21 -22 -23 -24 -25 -26 -27 -28
  Z28 +30 -29
  END
*MATERIAL
 1
 1
 0
 2
 2
 0
 3
 0
 2
 0
 0
 0
 2
 4
 2
 0
 0
 2
 2
 5
 5
 2
 0
 0
```

```
 0
 0
 0
 0
*********************** SOURCE ********************
ELECTRONS
ENERGY 15.0
**********************  OPTIONS  *******************
PULSE-HEIGHT  1 1
   NBINE 34 USER
14.99999 10.1 9.57 8.94 8.3 7.67 7.01 6.37 5.74 5.12 4.48 3.84
3.2 2.56 1.91 1.28
1.020 0.979 0.910 0.839 0.765 0.694 0.622 0.549 0.480
0.408 0.336 0.263 0.193 0.125 0.051 0.049 0.00001  0.0
ELECTRON-FLUX 1 1
   NBINE 19 USER
14.99999 1.020 0.979 0.910 0.839 0.765 0.694 0.622 0.549 0.480
0.408 0.336 0.263 0.193 0.125 0.051 0.049 0.00001  0.0
DOME-SOURCE  0. 0. 0.0 1.25
**********************  OPTIONS  *******************
CUTOFFS 0.1 0.01
HISTORIES 10000000
```

APPENDIX 3

CEASE Telescope - MCNPX Flat Disk Proton Source Runs

MCNPX Run 1. Disc source located at z=0.457 cm along telescope axis;
disk source radius = 0.025 cm;
9 MeV proton source
10,000 histories
Partial listing of output file: input file image, pulse height, flux, and energy deposition for cells 67 (DFT) and 88 (DBT)

```
Test for protons  CEASE Flight Sensor 9 MeV rad=0.025cm
C
C    Proton
C    transport - disk source, 9 MeV proton 40 deg slant  at z=.4572
```

GEOMETRY FILE DETAILS SAME AS SHOWN IN [FIRST YEAR REPORT]APPENDIX 3 OMITTED HERE FOR BREVITY

```
C
c       Transport protons, neutrons, muons, photons, pions, kaons,
c       deuterons, alphas

mode   h
cut:h    1.e+8  0.05
c    mode    h n | p /
c    Source definition, proton source (par=9), located on surface
c    #47 which is the plane at z=0.4572, centered at 0.,0.,0.4572,
c    with radius 0.025 cm, energy 9 MeV,40deg slant incidence (along z)
SDEF     sur=47 pos=0. 0. .4572  rad=D1 ERG=9.  WGT=1.0   par=9
         dir=0.7660444
SI1   .025
VOL     45J 0.144715 3J 4.501818 27J 0.1311943 21J 0.1333961
        2J 0.1129316 0.4679637  14J 19.61581 61.74832 5J
        139.2479  139.2432  103.1126 103.1126 103.1126
        103.1126  42J
c       No. of histories
NPS     10000
C
C    Materials
C
C        Brass
M1       29000 -.3   28000   -.7
C        Aluminum
M2       13027 -1.0
C        Tungsten
M3       74000 -.95 29000 -.015  28000 -.035
C        Gold
M4       79197 -1.0
C        Stainless Steel
M5       26000 -.71 29000 -.17 25055 -.065 28000 -.005 14000 -.05
C        Conductive Silicone Elastomer
M6       28000 -.377 47000 -.373 14000 -.0947
          6000 -.0810  8016 -.0539  1001 -.0204
C        PMMA
M7        6000 -.59985  8016 -.31961 1001 -.080538
C        Silicon
M8       14000 -1.0
C        Copper
M9       29000 -1.0
C
C
C
c     maximum proton energy(MeV) required for cross section table
PHYS:h 10.
c     maximum neutron energy(MeV) required for cross section table
PHYS:n 10.
c     maximum muon energy(MeV) required for cross section table
PHYS:| 10.
c     maximum photon energy(MeV) required for cross section table
PHYS:p 10.
c     maximum pion energy(MeV) required for cross section table
PHYS:/ 10.
c
```

```
c     Tallies
c     proton pulse height tallies
F8:h  67
E8 0 1.e-5 .5 1. 1.5 2. 2.3 3. 3.5 4. 4.5 5. 5.5 6. 6.5
        7. 7.5 8. 8.5 8.99999 9.
F38:h  88
E38 0 1.e-5 .5 1. 1.5 2. 2.3 3. 3.5 4. 4.5 5. 5.5 6. 6.5
        7. 7.5 8. 8.5 8.99999 9.
c     proton energy deposition tallies
*F18:h 67 88
c     proton flux tallies
F44:h    67 88
c     c   proton energy flux tallies
*F104:h    67 88
c     cell importances for protons
imp:h    1  165R    0 6R
c     cell importances for photons
c    imp:p    1  165R    0 6R
c     cell importances for neutrons
c     imp:n    1  165R    0 6R
c     cell importances for muons
c     imp:|    1  165R    0 6R
c     cell importances for pions
c     imp:/    1  165R    0 6R

1tally   8        nps =     10000
          tally type 8    pulse height distribution.                    units   number
          particle(s): proton
cell  67
     energy
   0.0000E+00    0.00000E+00 0.0000
   1.0000E-05    0.00000E+00 0.0000
   5.0000E-01    1.00000E-03 0.3161
   1.0000E+00    3.20000E-03 0.1765
   1.5000E+00    2.90000E-03 0.1854
   2.0000E+00    5.13000E-02 0.0430
   2.3000E+00    2.71000E-02 0.0599
   3.0000E+00    3.41000E-02 0.0532
   3.5000E+00    1.62000E-02 0.0779
   4.0000E+00    1.22000E-02 0.0900
   4.5000E+00    1.03000E-02 0.0980
   5.0000E+00    3.90000E-03 0.1598
   5.5000E+00    1.10000E-03 0.3013
   6.0000E+00    1.00000E-04 0.9999
   6.5000E+00    0.00000E+00 0.0000
   7.0000E+00    0.00000E+00 0.0000
   7.5000E+00    0.00000E+00 0.0000
   8.0000E+00    0.00000E+00 0.0000
   8.5000E+00    0.00000E+00 0.0000
   9.0000E+00    0.00000E+00 0.0000
   9.0000E+00    0.00000E+00 0.0000
     total       1.63400E-01 0.0226
          tally type 8*   energy deposition                             units   mev
          particle(s): proton
cell  67
                 4.15596E-01 0.0243

cell  88
                 2.61874E-02 0.1198
          tally type 8    pulse height distribution.                    units   number
          particle(s): proton
cell  88
     energy
   0.0000E+00    0.00000E+00 0.0000
   1.0000E-05    0.00000E+00 0.0000
   5.0000E-01    2.00000E-04 0.7070
   1.0000E+00    8.00000E-04 0.3534
   1.5000E+00    7.00000E-04 0.3778
   2.0000E+00    3.00000E-04 0.5773
   2.3000E+00    5.00000E-04 0.4471
   3.0000E+00    1.40000E-03 0.2671
   3.5000E+00    1.20000E-03 0.2885
   4.0000E+00    1.00000E-03 0.3161
   4.5000E+00    8.00000E-04 0.3534
   5.0000E+00    6.00000E-04 0.4081
   5.5000E+00    5.00000E-04 0.4471
   6.0000E+00    4.00000E-04 0.4999
   6.5000E+00    1.00000E-04 0.9999
   7.0000E+00    0.00000E+00 0.0000
   7.5000E+00    0.00000E+00 0.0000
```

```
   8.0000E+00    0.00000E+00 0.0000
   8.5000E+00    0.00000E+00 0.0000
   9.0000E+00    0.00000E+00 0.0000
   9.0000E+00    0.00000E+00 0.0000
     total       8.50000E-03 0.1080
          tally type 4    track length estimate of particle flux.      units   1/cm**2
          particle(s): proton

          volumes
                  cell:       67           88
                        7.61920E-03  4.23017E-02
 cell  67
                 3.57828E-01 0.0241
 cell  88
                 2.20099E-03 0.1326
          tally type 4*   track length estimate of energy flux.        units   mev/cm**2
          particle(s): proton
          volumes
                  cell:       67           88
                        7.61920E-03  4.23017E-02
 cell  67
                 2.02689E+00 0.0268
 cell  88
                 5.68473E-03 0.1553Test for protons  CEASE Flight Sensor 9 MeV
rad=0.025cm
C
```

MCNPX Run 2. Disc source located at z=0.457 cm along telescope axis;
disk source radius = 0.050 cm;
9 MeV proton source
40,000 histories
Partial listing of output file: input file image, pulse height, flux, and energy deposition for cells 67 (DFT) and 88 (DBT)

```
    1-       Test for protons  CEASE Flight Sensor 9 MeV rad=0.05cm
    2-       C
    3-       C    Proton
    4-       C    transport - disk source, 9 MeV proton 40 deg slant  at z=.4572
    5-       C
  462-       C
  463-       c       Transport protons, neutrons, muons, photons, pions, kaons,
  464-       c       deuterons, alphas
  465-
  466-       mode    h
  467-       cut:h    1.e+8   0.05
  468-       c    mode     h n | p /
  469-       c    Source definition, proton source (par=9), located on surface
  470-       c    #47 which is the plane at z=0.4572, centered at 0.,0.,0.4572,
  471-       c    with radius 0.05 cm, energy 9 MeV,40deg slant incidence (along z)
  472-       SDEF     sur=47 pos=0. 0. .4572  rad=D1 ERG=9.  WGT=1.0    par=9
  473-                dir=0.7660444
  474-       SI1   .05
  475-       VOL    45J 0.144715 3J 4.501818 27J 0.1311943 21J 0.1333961
  476-              2J 0.1129316 0.4679637  14J 19.61581 61.74832 5J
  477-              139.2479  139.2432  103.1126 103.1126 103.1126
  478-              103.1126  42J
  479-       c      No. of histories
  480-       NPS    40000
  481-       C
```

```
c   Materials
c
c       Brass
M1      29000 -.3  28000  -.7
c       Aluminum
M2      13027 -1.0
c       Tungsten
M3      74000 -.95 29000 -.015  28000 -.035
c       Gold
M4      79197 -1.0
c       Stainless Steel
M5      26000 -.71 29000 -.17 25055 -.065 28000 -.005 14000 -.05
c       Conductive Silicone Elastomer
M6      28000 -.377 47000 -.373 14000 -.0947
         6000 -.0810  8016 -.0539  1001 -.0204
c       PMMA
M7       6000 -.59985  8016 -.31961 1001 -.080538
c       Silicon
M8      14000 -1.0
c       Copper
M9      29000 -1.0
c
c
c
c    maximum proton energy(MeV) required for cross section table
PHYS:h 10.
c    maximum neutron energy(MeV) required for cross section table
PHYS:n 10.
c    maximum muon energy(MeV) required for cross section table
PHYS:| 10.
c    maximum photon energy(MeV) required for cross section table
PHYS:p 10.
c    maximum pion energy(MeV) required for cross section table
PHYS:/ 10.
c
c    Tallies
c    proton pulse height tallies
F8:h  67
E8 0 1.e-5 .5 1. 1.5 2. 2.3 3. 3.5 4. 4.5 5. 5.5 6. 6.5
       7. 7.5 8. 8.5 8.99999 9.
F38:h  88
E38 0 1.e-5 .5 1. 1.5 2. 2.3 3. 3.5 4. 4.5 5. 5.5 6. 6.5
       7. 7.5 8. 8.5 8.99999 9.
c    proton energy deposition tallies
*F18:h 67 88
c     proton flux tallies
F44:h   67 88
c     c   proton energy flux tallies
*F104:h   67 88
c    cell importances for protons
imp:h   1  165R   0 6R
c    cell importances for photons
c   imp:p   1  165R   0 6R
c    cell importances for neutrons
c    imp:n   1  165R   0 6R
c    cell importances for muons
c    imp:|   1  165R   0 6R
c    cell importances for pions
c    imp:/   1  165R   0 6R
```

```
1tally   8         nps =     40000
           tally type 8    pulse height distribution.                     units   number
           particle(s): proton

 cell  67
      energy
   0.0000E+00    0.00000E+00 0.0000
   1.0000E-05    0.00000E+00 0.0000
   5.0000E-01    5.75000E-04 0.2085
   1.0000E+00    1.45000E-03 0.1312
   1.5000E+00    1.90000E-03 0.1146
   2.0000E+00    1.49500E-02 0.0406
   2.3000E+00    1.01750E-02 0.0493
   3.0000E+00    1.61250E-02 0.0391
   3.5000E+00    7.27500E-03 0.0584
   4.0000E+00    5.50000E-03 0.0672
   4.5000E+00    4.72500E-03 0.0726
   5.0000E+00    1.80000E-03 0.1177
   5.5000E+00    2.00000E-04 0.3535
   6.0000E+00    0.00000E+00 0.0000
```

```
   6.5000E+00    0.00000E+00 0.0000
   7.0000E+00    0.00000E+00 0.0000
   7.5000E+00    0.00000E+00 0.0000
   8.0000E+00    0.00000E+00 0.0000
   8.5000E+00    0.00000E+00 0.0000
   9.0000E+00    2.50000E-05 1.0000
   9.0000E+00    0.00000E+00 0.0000
     total       6.47000E-02 0.0190
          tally type 8*   energy deposition                         units    mev
          particle(s): proton
cell  67
                 1.69238E-01 0.0202
cell  88
                 1.30129E-02 0.0846
          tally type 8    pulse height distribution.                units    number
          particle(s): proton
cell  88
     energy
   0.0000E+00    0.00000E+00 0.0000
   1.0000E-05    0.00000E+00 0.0000
   5.0000E-01    2.50000E-04 0.3162
   1.0000E+00    3.00000E-04 0.2886
   1.5000E+00    3.00000E-04 0.2886
   2.0000E+00    5.00000E-04 0.2236
   2.3000E+00    2.50000E-04 0.3162
   3.0000E+00    9.25000E-04 0.1643
   3.5000E+00    4.75000E-04 0.2294
   4.0000E+00    3.00000E-04 0.2886
   4.5000E+00    3.25000E-04 0.2773
   5.0000E+00    3.00000E-04 0.2886
   5.5000E+00    2.50000E-04 0.3162
   6.0000E+00    2.00000E-04 0.3535
   6.5000E+00    7.50000E-05 0.5773
   7.0000E+00    0.00000E+00 0.0000
   7.5000E+00    0.00000E+00 0.0000
   8.0000E+00    0.00000E+00 0.0000
   8.5000E+00    0.00000E+00 0.0000
   9.0000E+00    0.00000E+00 0.0000
   9.0000E+00    0.00000E+00 0.0000
     total       4.45000E-03 0.0748
          tally type 4    track length estimate of particle flux.   units    1/cm**2
          particle(s): proton
          volumes
                    cell:        67              88
                           7.61920E-03   4.23017E-02
cell  67
                 1.35987E-01 0.0203
cell  88
                 1.08395E-03 0.0956
          tally type 4*   track length estimate of energy flux.     units    mev/cm**2
          particle(s): proton
          volumes
                    cell:        67              88
                           7.61920E-03   4.23017E-02
cell  67
                 7.09309E-01 0.0227
cell  88
                 2.81644E-03 0.1149
```

APPENDIX 4

MCNPX Output File for Grazing Angle Proton Scattering Study

250 keV Proton Beam Incident on Iridium Slab, Angle of Incidence = 0.1°

```
1mcnpx    version 2.1.5 ld=Fri May 21 09:49:28 MDT 1999                   11/21/01 11:48:39
**************************************************************************************    probid =   11/21/01 11:48:39
 inp=ird250p1 out=oir250p1

                          *
                          *
                          *
                          *
                          *
   1-       Grazing incident proton beam on Iridium slab  250 keV
   2-       C      Cells
   3-       c     Iridium slab
   4-       1     1 -22.42 1 -2 3 -4 5 -6
   5-       c     Void region above slab
   6-       2     0  2 -7 3 -4 5 -6
   7-       c     escape
   8-       3     0  -1:7:-3:4:-5:6
   9-
  10-       c      Surfaces
  11-       1       pz  -1.0
  12-       2       pz  0.0
  13-       3       px  -3.0
  14-       4       px  3.0
  15-       5       py  -1.0
  16-       6       py  4.0
  17-       7       pz  1.0
  18-       c
  19-
  20-       c     Transport protons
  21-       mode     h
  22-       c
  23-       c     Source defined by subroutine srcoblq.F is a monodirectional
  24-       c     beam source grazing incidence 90.1 degrees off normal
  25-       c     Energy is 0.25 MeV
  26-       c
  27-       c
  28-       c   no. of histories
```

```
nps     100000000
c
c         proton cutoff energy 1.0 keV
cut:h     1.e+10 0.001
c
c       materials
c
c       iridium
M1        77000 -1.0
c         maximum proton energy(MeV) needed for cross sections
phys:h  2.
c    tallies
c       proton current (reflected) emerging from surface 2 (z=0.0)
F1:h      2
c       emergent polar angle cosine bins
C1        0.0          0.17453E-02 0.34906E-02 0.52359E-02 0.69812E-02
          0.87265E-02 0.10472E-01 0.12217E-01 0.13962E-01 0.15707E-01
          0.17452E-01 0.19197E-01 0.20942E-01 0.22687E-01 0.24432E-01
          0.26177E-01 0.27922E-01 0.29666E-01 0.31411E-01 0.33155E-01
          0.34899E-01 0.36644E-01 0.38388E-01 0.40132E-01 0.41876E-01
          0.43619E-01 0.45363E-01 0.47106E-01 0.48850E-01 0.50593E-01
          0.52336E-01 0.54079E-01 0.55821E-01 0.57564E-01 0.59306E-01
          0.61048E-01 0.62790E-01 0.64532E-01 0.66274E-01 0.68015E-01
          0.69756E-01 0.71497E-01 0.73238E-01 0.74979E-01 0.76719E-01
          0.78459E-01 0.80199E-01 0.81938E-01 0.83678E-01 0.85417E-01
          0.87156E-01 0.17365E+00 0.25882E+00 0.34202E+00 0.42262E+00
          0.50000E+00 0.57358E+00 0.64279E+00 0.70711E+00 0.76604E+00
          0.81915E+00 0.86603E+00 0.90631E+00 0.93969E+00 0.96593E+00
          0.98481E+00 0.99619E+00 0.10000E+01
c       emergent energy bins (MeV)
E1       .0125 .025 .0375 .05 .0625 .075 .0875 .1 .1125 .125 .1375
         .15 .1625  .175   .1875   .2   .2125  .225  .2375  0.25
F11:h    2
E11      .0125 .025 .0375 .05 .0625 .075 .0875 .1 .1125 .125 .1375
         .15 .1625  .175   .1875   .2   .2125  .225  .2375  0.25
c11        0. 1.
c        cell importances for protons
imp:h     1 1  0
ptrac file=asc write=all
        filter=-1.e-10,1.e-10,z 0,1,w max=100000 nps=1,100000
```

PTRAC file
written to
extract
emergent
proton
azimuthal angle

```
warning.  no cross-section tables are called for in this problem.

 MCNPX particle types:  kpt() =
  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

```
 LAHET energy cutoff setings:
 emin() =
   1.00000E-03    1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30
   1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30
   1.00000E+30    1.00000E+30    1.00000E-03    1.00000E+30    1.00000E+30    1.00000E+30    1.00000E+30
   1.00000E+30

1LAHET physics options:                                                                    print table 41

 1ca    ielas   ipreq  iexisa  ichoic   jcoul  nexite   npidk   noact    icem
 1ca        2       1       1      23       1       1       0       1       0

 1cb    flenb(i),i=1,6                                                     ctofe       flim0
 1cb    3.4900E+03  3.4900E+03  2.4900E+03  2.4900E+03  8.0000E+02  8.0000E+02 -1.0000E+00 -1.0000E+00

 1ea     ipht     icc  nobalc  nobale   ifbrk  ilvden   ievap   nofis
 1ea        1       4       1       0       1       0       0       1

 1eb    yzere       bzere       yzero       bzero
 1eb    1.5000E+00  8.0000E+00  1.5000E+00  1.0000E+01

1cells                                                                             print table 60

                    atom        gram                                           proton
       cell  mat   density     density     volume       mass       pieces  importance

    1     1    1  7.02409E-02 2.24200E+01 3.00000E+01 6.72600E+02       0  1.0000E+00
    2     2    0  0.00000E+00 0.00000E+00 3.00000E+01 0.00000E+00       0  1.0000E+00
    3     3    0  0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00       0  0.0000E+00

 total                                    6.00000E+01 6.72600E+02
          1 warning message so far.
decimal words of dynamically allocated storage
     general                37806
     tallies                31228
     bank                   19703
     cross sections             0

     total                  81009      =      324036 bytes
     available (mdas)     4000000
1problem summary
      run terminated when 100000000 particle histories were done.
                                                                                     11/22/01 18:52:54
+
      Grazing incident proton beam on Iridium slab  250 keV                 probid =  11/21/01 11:48:39
0
 proton creation         tracks   weight        energy          proton loss          tracks   weight        energy
                                  (per source particle)                                       (per source particle)
```

```
source               100000000    1.0000E+00    2.5000E-01           escape              85340666    8.5341E-01    1.9430E-01
nucl. interaction            0    0.            0.                   energy cutoff       14659334    1.4659E-01    1.4659E-04
particle decay               0    0.            0.                   time cutoff                0    0.            0.
weight window                0    0.            0.                   weight window              0    0.            0.
cell importance              0    0.            0.                   cell importance            0    0.            0.
weight cutoff                0    0.            0.                   weight cutoff              0    0.            0.
energy importance            0    0.            0.                   energy importance          0    0.            0.
dxtran                       0    0.            0.                   dxtran                     0    0.            0.
forced collisions            0    0.            0.                   forced collisions          0    0.            0.
exp. transform               0    0.            0.                   exp. transform             0    0.            0.
tabular sampling             0    0.            0.                   multiple scatter           0    0.            5.5550E-02
                                                                     bremsstrahlung             0    0.            0.
                                                                     nucl. interaction          0    0.            0.
elastic recoil               0    0.            0.                   elastic scatter            0    0.            0.
                                                                     particle decay             0    0.            0.
    total            100000000    1.0000E+00    2.5000E-01               total          100000000    1.0000E+00    2.5000E-01

computer time so far in this run  1596.25 minutes             maximum number ever in bank          0
computer time in mcrun            1596.23 minutes             bank overflows to backup file        0
source particles per minute           6.2647E+04              dynamic storage      81013 words,      324052 bytes.
random numbers generated             53634305630              most random numbers used was      4326 in history 70074867

range of sampled source weights = 1.0000E+00 to 1.0000E+00
1proton      activity in each cell                                                                              print table 126

                tracks      population    substeps     substeps      number        flux        average       average
       cell    entering                               * weight     weighted     weighted    track weight    track mfp
                                                    (per history)    energy       energy     (relative)       (cm)

    1     1   100000000    100000000  10796091450    1.0796E+02   9.0610E-02   1.3716E-01   1.0000E+00   4.4749E-07
    2     2   185340666    100000000            0    0.0000E+00   2.3315E-01   2.3746E-01   1.0000E+00   0.0000E+00

    total     285340666    200000000  10796091450    1.0796E+02
1tally   1         nps =100000000
          tally type 1    number of particles crossing a surface.
          particle(s): proton


 surface  2
 cosine bin:  -1.          to  0.00000E+00
      energy
   1.2500E-02   0.00000E+00 0.0000
   2.5000E-02   0.00000E+00 0.0000
   3.7500E-02   0.00000E+00 0.0000

   5.0000E-02   0.00000E+00 0.0000
   6.2500E-02   0.00000E+00 0.0000
```

```
   7.5000E-02    0.00000E+00 0.0000
   8.7500E-02    0.00000E+00 0.0000
   1.0000E-01    0.00000E+00 0.0000
   1.1250E-01    0.00000E+00 0.0000
   1.2500E-01    0.00000E+00 0.0000
   1.3750E-01    0.00000E+00 0.0000
   1.5000E-01    0.00000E+00 0.0000
   1.6250E-01    0.00000E+00 0.0000
   1.7500E-01    0.00000E+00 0.0000
   1.8750E-01    0.00000E+00 0.0000
   2.0000E-01    0.00000E+00 0.0000
   2.1250E-01    0.00000E+00 0.0000
   2.2500E-01    0.00000E+00 0.0000
   2.3750E-01    0.00000E+00 0.0000
   2.5000E-01    1.00000E+00 0.0000
     total       1.00000E+00 0.0000

surface  2
cosine bin:    0.00000E+00 to  1.74530E-03
     energy
   1.2500E-02    2.00000E-07 0.2236
   2.5000E-02    3.80000E-07 0.1622
   3.7500E-02    4.40000E-07 0.1508
   5.0000E-02    4.20000E-07 0.1543
   6.2500E-02    2.50000E-07 0.2000
   7.5000E-02    4.60000E-07 0.1474
   8.7500E-02    3.20000E-07 0.1768
   1.0000E-01    5.30000E-07 0.1374
   1.1250E-01    5.30000E-07 0.1374
   1.2500E-01    7.10000E-07 0.1187
   1.3750E-01    9.00000E-07 0.1054
   1.5000E-01    1.37000E-06 0.0854
   1.6250E-01    2.15000E-06 0.0682
   1.7500E-01    3.09000E-06 0.0569
   1.8750E-01    4.77000E-06 0.0458
   2.0000E-01    8.66000E-06 0.0340
   2.1250E-01    1.58700E-05 0.0251
   2.2500E-01    4.20900E-05 0.0154
   2.3750E-01    1.69720E-04 0.0077
   2.5000E-01    5.60627E-03 0.0013
     total       5.85913E-03 0.0013
                     *
                     *
                     *
                     *
                     *
                     *
```

20 energy bins

Angle bin #1, 0°-0.1°
(cosine shown is $\cos(\pi/2-\theta)$

```
surface  2
cosine bin:   9.84810E-01 to  9.96190E-01
      energy
   1.2500E-02   1.56000E-05 0.0253
   2.5000E-02   7.27300E-05 0.0117
   3.7500E-02   1.13430E-04 0.0094
   5.0000E-02   1.30160E-04 0.0088
   6.2500E-02   1.20160E-04 0.0091
   7.5000E-02   9.04100E-05 0.0105
   8.7500E-02   5.75000E-05 0.0132
   1.0000E-01   2.97200E-05 0.0183
   1.1250E-01   1.18700E-05 0.0290
   1.2500E-01   3.82000E-06 0.0512
   1.3750E-01   9.30000E-07 0.1037
   1.5000E-01   1.10000E-07 0.3015
   1.6250E-01   1.00000E-08 1.0000
   1.7500E-01   0.00000E+00 0.0000
   1.8750E-01   0.00000E+00 0.0000
   2.0000E-01   0.00000E+00 0.0000
   2.1250E-01   0.00000E+00 0.0000
   2.2500E-01   0.00000E+00 0.0000
   2.3750E-01   0.00000E+00 0.0000
   2.5000E-01   0.00000E+00 0.0000
      total     6.46450E-04 0.0039
```

Angle bin #68,
85°-90°

```
surface  2
cosine bin:   9.96190E-01 to  1.00000E+00
      energy
   1.2500E-02   5.49000E-06 0.0427
   2.5000E-02   2.38600E-05 0.0205
   3.7500E-02   3.82600E-05 0.0162
   5.0000E-02   4.36400E-05 0.0151
   6.2500E-02   4.06900E-05 0.0157
   7.5000E-02   2.92400E-05 0.0185
   8.7500E-02   1.79600E-05 0.0236
   1.0000E-01   8.39000E-06 0.0345
   1.1250E-01   3.58000E-06 0.0529
   1.2500E-01   9.50000E-07 0.1026
   1.3750E-01   1.80000E-07 0.2357
   1.5000E-01   4.00000E-08 0.5000
   1.6250E-01   0.00000E+00 0.0000
   1.7500E-01   0.00000E+00 0.0000
   1.8750E-01   0.00000E+00 0.0000
   2.0000E-01   0.00000E+00 0.0000
   2.1250E-01   0.00000E+00 0.0000
   2.2500E-01   0.00000E+00 0.0000
   2.3750E-01   0.00000E+00 0.0000
```

```
   2.5000E-01    0.00000E+00 0.0000
     total       2.12280E-04 0.0069

                      *
                      *
                      *
                      *
                      *

                      *

          tally type 1    number of particles crossing a surface.
          particle(s): proton

surface  2
cosine bin:  -1.          to  0.00000E+00
     energy
   1.2500E-02    0.00000E+00 0.0000
   2.5000E-02    0.00000E+00 0.0000
   3.7500E-02    0.00000E+00 0.0000
   5.0000E-02    0.00000E+00 0.0000
   6.2500E-02    0.00000E+00 0.0000
   7.5000E-02    0.00000E+00 0.0000
   8.7500E-02    0.00000E+00 0.0000
   1.0000E-01    0.00000E+00 0.0000
   1.1250E-01    0.00000E+00 0.0000
   1.2500E-01    0.00000E+00 0.0000

   1.3750E-01    0.00000E+00 0.0000
   1.5000E-01    0.00000E+00 0.0000
   1.6250E-01    0.00000E+00 0.0000
   1.7500E-01    0.00000E+00 0.0000
   1.8750E-01    0.00000E+00 0.0000
   2.0000E-01    0.00000E+00 0.0000
   2.1250E-01    0.00000E+00 0.0000
   2.2500E-01    0.00000E+00 0.0000
   2.3750E-01    0.00000E+00 0.0000
   2.5000E-01    1.00000E+00 0.0000
     total       1.00000E+00 0.0000

surface  2
cosine bin:   0.00000E+00 to  1.00000E+00
     energy
   1.2500E-02    6.56210E-04 0.0039
   2.5000E-02    2.65809E-03 0.0019
   3.7500E-02    4.23233E-03 0.0015
```

Sum over all angle bins

```
 5.0000E-02   4.96509E-03 0.0014
 6.2500E-02   5.44576E-03 0.0014
 7.5000E-02   5.55055E-03 0.0013
 8.7500E-02   5.79733E-03 0.0013
 1.0000E-01   5.91880E-03 0.0013
 1.1250E-01   6.39339E-03 0.0012
 1.2500E-01   6.80390E-03 0.0012
 1.3750E-01   7.32951E-03 0.0012
 1.5000E-01   8.16091E-03 0.0011
 1.6250E-01   9.29315E-03 0.0010
 1.7500E-01   1.08095E-02 0.0010
 1.8750E-01   1.28450E-02 0.0009
 2.0000E-01   1.61703E-02 0.0008
 2.1250E-01   2.21435E-02 0.0007
 2.2500E-01   3.40218E-02 0.0005
 2.3750E-01   6.65577E-02 0.0004
 2.5000E-01   6.17654E-01 0.0001
   total      8.53407E-01 0.0000
                    *
                    *
                    *
                    *
                    *
                    *

run terminated when 100000000 particle histories were done.

computer time = 1596.25 minutes

mcnpx    version 2.1.5 Fri May 21 09:49:28 MDT 1999              11/22/01 18:52:55     probid =    11/21/01 11:48:39
```

APPENDIX 5

MCNPX Source Subroutine for Grazing Angle Proton Scattering Study

```
c_deck so source
so          1
      subroutine source
so          2
c   user supplied source subroutine
#include "cm.h"
c
c      This is the source routine for oblique proton beams
c      incident on Al or Ir slab
c      The name of this deck is srcoblq.F
c
      data pin/3.14159265/
      data komin/0/
      if(komin.eq.0)then
      komin=1
      open(47,form='unformatted',status='scratch')
      write(jtty,20)
20    format(1x,'Enter source energy (MeV) and incident
obliquity (deg.)
     $')
c     example, 2 degree obliquity means enter 92.0 deg (i.e.
92 deg off normal)
      read(itty,*)erg,obliq
      write(47)erg,obliq
      write(jtty,21)erg,obliq
      write(iuo,21)erg,obliq
21    format(1x,'Source energy (MeV)=',e12.5,2x,'Incident
obliquity (deg
     $.) =',e12.5)
      rewind 47
      end if
      wgt=1.0
      tme=0.0
      read(47)erg,obliq
      rewind 47
c
c     The source energy
c      erg= 0.1
c     ipt=9 denotes proton source.
c
      ipt=9
c     incident grazing obliquity 92 degrees off normal (2
degrees off surface)
      ths=obliq/180.*pin
      sths=sin(ths)
      cths=cos(ths)
c     incident azimuth = 90 degrees
      phs=0.5*pin
      sphs=1.0
      cphs=0.0
```

```
c     direction cosines of incident beam
      uuu=sths*cphs
      vvv=sths*sphs
      www=cths
      aa=sqrt(uuu**2+vvv**2+www**2)
      uuu=uuu/aa
      vvv=vvv/aa
      www=www/aa
c     point of source incidence
      xxx=0.0
      yyy=-0.99
      zzz=yyy*cths/sths
      jsu=0
      icl=2
      do 50 ispr=1,3
50    spare(ispr)=0.0
      return
      end
```

APPENDIX 6

PHILOOK, Program for Extraction and Conversion to Histogram Form of Emergent Proton Azimuthal Distributions from MCNPX PTRAC File Output Produced in the Grazing Angle Proton Scattering Study

```
      implicit real*8 (a-h,o-z)
      dimension phibin(60),count(60),a(200),b(200)
      character*120 line
      data pye/3.14159265/
      data count/60*0./
      open(2,file='lookit',status='unknown')
      open(7,file='bin1',status='unknown')
      write(6,1)
1     format(1x,'Enter number of phi bins and number of
histories')
      read(5,*)nbins,hists
      dphi=360./nbins
      write(6,17)nbins
17    format(1x,i5)
      phibin(1)=dphi
      do 10 n=2,nbins
10    phibin(n)=phibin(n-1)+dphi
      fac=180./pye
      open(1,file='ptrac',status='old')
      do 20 i=1,10
20      read(1,2)line
2     format(a)
100   read(1,2,end=200)line
      read(1,2)line
      read(1,*)x,y,z,u,v,w,e,wt,t
      sth=sqrt(1.-w*w)
      if(sth.eq.0.)go to 100
      cphi=u/sth
      sphi=v/sth
      if(cphi.ge.0. .and. sphi.ge.0.)kq=1
      if(cphi.ge.0. .and. sphi.lt.0.)kq=4
      if(cphi.lt.0. .and. sphi.ge.0.)kq=2
      if(cphi.lt.0. .and. sphi.lt.0.)kq=3
      if(abs(sphi-1.0).le.1.e-5)kq=5
      if(kq.eq.5)phi=0.5*pye
      if(kq.eq.1)phi=asin(abs(sphi))
      if(kq.eq.2)phi=pye-asin(abs(sphi))
      if(kq.eq.3)phi=pye+asin(abs(sphi))
      if(kq.eq.4)phi=2.*pye-asin(abs(sphi))
      phid=fac*phi
      do 30 n=1,nbins
```

```
      if(phid.gt.phibin(n))go to 30
      ibin=n
      if(ibin.eq.1)write(7,77)x,y,z,u,v,w,sphi,cphi
77    format(1x,8e16.9)
      count(ibin)=count(ibin)+1.
      go to 100
30    continue
200   do 210 n=1,nbins
      count(n)=count(n)/hists
210   write(2,4)n,phibin(n),count(n)
4     format(1x,'bin no.=',i5,1x,'upper
bound(deg.)=',f7.2,1x,'count=',e
     $12.5)
      i=1
      a(1)=0.
      b(1)=count(1)
      nb1=nbins-1
      do 215 n=1,nb1
      i=i+1
      a(i)=phibin(n)
      b(i)=count(n)
      i=i+1
      a(i)=phibin(n)
215   b(i)=count(n+1)
      ii=i+1
      a(ii)=360.
      b(ii)=b(1)
      do 220 i=1,ii
220   write(2,5)a(i),b(i)
5     format(1x,f7.1, 2x,e12.5)
      close (1)
      close (2)
      stop
      end
```